

PROJECTION OPTICAL SYSTEM AND  
PROJECTION EXPOSURE APPARATUS

FIELD OF THE INVENTION AND RELATED ART

5           This invention relates to a projection  
optical system and a projection exposure apparatus for  
projecting a pattern of a mask onto a substrate  
through the projection optical system. More  
particularly, the invention concerns a catadioptric  
10 projection optical system having a reflection mirror,  
for printing, by projection exposure, a reticle  
pattern on a semiconductor wafer.

          The density of an integrated circuit  
increases more and more, and the specification and  
15 performance required for a projection (exposure)  
optical system become much strict. Generally, in  
order to obtain a higher resolving power, the exposure  
wavelength is shortened and/or the numerical aperture  
(NA) of a projection optical system is enlarged.

20           However, as the exposure wavelength reaches a  
region of 193 nm (ArF excimer laser light) or 157 nm  
(F<sub>2</sub> excimer laser light), usable lens materials are  
limited to quartz and fluorite. This is mainly  
because of decreases of the light transmission factor.  
25 For example, in a projection optical system such as  
disclosed in Japanese Laid-Open Patent Application,  
Laid-Open No. 79345/1995, wherein it comprises all

dioptric lenses of a large number and wherein all lenses have a large glass material thickness, the exposure amount on a wafer becomes low and it causes a decrease of the throughput. Also, due to thermal absorption by lenses, there occur problems (thermal aberration) such as changes of aberration or shift of the focal point position. Where the exposure wavelength is 193 nm, quartz and fluorite can be used as a projection optical system. However, because the difference in dispersion between them is not large, correction of chromatic aberration is difficult to accomplish. In order to correct the chromatic aberration of a projection optical system completely, it is necessary to use a few achromatic lenses having a small curvature radius at its achromatic surface. This leads to an increase of the total glass material thickness of the optical system, which then raises the above-described problems of thermal aberration and transmission factor. Further, currently, it is very difficult to produce a projection optical system by use of fluorite, having a sufficient property to assure its design performance. It is further difficult to produce one having a large diameter. This makes it very difficult to accomplish color correction, and results in an increase of the cost. As for the exposure wavelength of 157 nm, only fluorite is the usable lens material. The chromatic

aberration can not be corrected only with a single lens material. Any way, it is very difficult to provide a projection optical system only by use of dioptric systems.

5 In consideration of these inconveniences, many proposals have been made to introduce a reflecting system, having a mirror, into an optical system to thereby avoid the problems of transmission factor and color correction. For example, Japanese  
10 Laid-Open Patent Applications, Laid-Open Nos. 211332/1997 and 90602/1998 show a catoptric projection optical system which is constituted only by use of reflecting systems. Further, U.S. Patent No. 5,650,877 and Japanese Laid-Open Patent Applications,  
15 Laid-Open Nos. 210415/1987, 258414/1987, 163319/1988, 66510/1990, 282527/1991, 234722/1992, 188298/1993, 230287/1994, and 304705/1996 show a catadioptric projection optical system having a combination of catoptric and dioptric systems.

20 Where a projection optical system which includes a catoptric system to meet the shortening of the exposure wavelength and the enlargement of NA (numerical aperture) is produced, the structure should of course be one that enables correction of chromatic  
25 aberration. In addition, idealistically, the structure should be simple and enough to enable that an imaging region of sufficient size is defined upon

an image plane, that the number of optical elements such as mirrors or lenses is small, that the mirror incidence angle and reflection angle are not large, and that a sufficient image-side working distance is assured.

If an imaging region width of sufficient size is attainable on the image plane, in the case of a scan type projection exposure apparatus, it is advantageous in respect to the throughput, such that the exposure variation can be suppressed. If the number of optical elements is small, the process load in the production of optical elements such as mirrors and lenses can be reduced. Also, since the total glass material thickness can be made smaller, the loss of light quantity can be reduced. Further, the increase of the footprint of the apparatus can be suppressed, and the loss of light quantity due to the film can also be decreased. Particularly, this is very advantageous because, where the exposure wavelength is 157 nm ( $F_2$  excimer laser light), the loss of light quantity at the mirror reflection film can not be disregarded. Where the mirror incidence angle and reflection angle are not large, the influence of a change in light quantity due to the angular characteristic of the reflection film can be suppressed. If a sufficient image-side working distance can be maintained, it is advantageous in

respect to structuring an autofocus system or a wafer stage conveyance system in the apparatus. If the structure is simple, complicatedness of a mechanical barrel, for example, can be avoided, and it provides an advantage to the manufacture.

Here, the conventional examples are considered in respect to the above-described points.

In the projection optical system shown in U.S. Patent No. 5,650,877, a Mangin mirror and a refracting member are disposed in an optical system to print an image of a reticle on a wafer. This optical system has inconveniences that, in every picture angle used, there occurs light interception (void) at the central portion of a pupil and that the exposure region can not be made large. If the exposure region is to be enlarged, it disadvantageously causes widening of the light interception at the central portion of the pupil. Further, the refractive surface of the Mangin mirror defines a beam splitting surface such that the light quantity decreases to a half each time the light passes this surface. The light quantity will be decreased to about 10% upon the image plane (wafer surface).

In the projection optical systems shown in Japanese Laid-Open Patent Applications, Laid-Open Nos. 211332/1997 and 90602/1998, the basic structure comprises a reflection system only. However, in

respect to aberration (Petzval sum) and mirror disposition, it is difficult to keep sufficient imaging region width on the image plane. Also, since in this structure a concave mirror adjacent the image plane and having a large power mainly has an imaging function, enlargement of NA is difficult to accomplish. Since a convex mirror is placed just before the concave mirror, a sufficient image-side working distance can not be maintained.

In the projection optical systems shown in Japanese Laid-Open Patent Applications, Laid-Open Nos. 210415/1987 and 258414/1987, a Cassegrain type or Schwarzschild type mirror system is used. An opening is formed at the central portion of the mirror, by which a void is defined in the pupil such that only the peripheral portion of the pupil contributes to the imaging. However, the presence of a void in the pupil will have an influence on the imaging performance. If the pupil void is to be made smaller, the power of the mirror must be large. This causes enlargement of the incidence and reflection angles of the mirror. Further, an enlarged NA (numerical aperture) will cause a large increase of the mirror diameter.

In the projection optical systems shown in Japanese Laid-Open Patent Applications, Laid-Open Nos. 163319/1988, 188298/1993 and 230287/1994, the structure is complicated due to deflection and bend of

the optical path. Since most of the power of optical groups for imaging an intermediate image, as a final image, is sustained by a concave mirror, it is structurally difficult to enlarge the NA. The magnification of the lens system which is disposed between the concave mirror and the image plane is at a reduction ratio and also it has a positive sign. Because of it, a sufficient image-side working distance can not be kept. Further, in order that the object plane and the image plane are placed opposed, it is necessary to use two flat mirrors only for the sake of deflection of the optical path, without any contribution to aberration correction. As the exposure wavelength is shorted to 157 nm, this is undesirable also in respect to the loss of light quantity. Further, it is structurally difficult to hold the imaging region width because of the necessity of light path division. Since the optical system has to be large, there is a disadvantage in respect to the footprint.

In the projection optical systems shown in Japanese Laid-Open Patent Applications, Laid-Open Nos. 66510/1990 and 282527/1991, the optical path is divided by a beam splitter, and this makes the barrel structure complicated. It needs a beam splitter of large diameter and, if this is of a prism type, the loss of light quantity is large because of its

thickness. For a larger NA, a larger diameter is necessary, and thus the loss of light quantity becomes larger. If the beam splitter is of a flat plate type, there will occur astigmatism and comma even in regard to axial light rays. Further, there may occur aberrations due to a change in characteristic at the light dividing surface or production of asymmetric aberration resulting from thermal absorption. It is therefore difficult to manufacture the beam splitter very accurately.

In the projection optical systems shown in Japanese Laid-Open Patent Applications, Laid-Open Nos. 234722/1992 and 304705/1996, many of the above-described inconveniences may be removed. However, each time the optical path is deflected, the light path from a concave mirror is divided. This requires eccentric optical handling and it makes the structure and assembling very complicated.

#### SUMMARY OF THE INVENTION

It is accordingly an object of the present invention to provide a projection optical system of simple structure and easy assembling wherein an optical system such as disclosed in Japanese Laid-Open Patent Applications, Laid-Open Nos. 234722/1992 and 304705/1996, described above, is improved. It is another object of the present invention to provide a



projection exposure apparatus and/or a device  
manufacturing method using the same.

In accordance with the present invention, a  
projection optical system, a projection exposure  
5 apparatus and a device manufacturing method having  
features as stated in Items (1) - (37) below are  
provided.

(1) A projection optical system for projecting an  
image of an object onto an image plane, comprising: a  
10 first imaging optical system for forming an image of  
the object; a second imaging optical system for re-  
imaging the image upon the image plane; wherein said  
first and second imaging optical systems are disposed  
in an order from the object side and are disposed  
15 along a common straight optical axis, wherein said  
first imaging optical system includes a first mirror  
for reflecting and collecting abaxial light from the  
object, wherein one of said first and second imaging  
optical systems includes a second mirror for  
20 reflecting light from said first mirror to the image  
plane side, and wherein, with said second mirror, the  
abaxial light is caused to pass an outside of an  
effective diameter of said first mirror.

(2) A projection optical system according to Item  
25 (1) wherein said first imaging optical system has a  
magnification  $\beta$  which satisfies a relation  $|\beta| \geq 1$ .

(3) A projection optical system according to Item

(1) or (2) wherein said first imaging optical system includes at least one lens.

(4) A projection optical system according to Item (3) wherein said lens has a positive refracting power.

5 (5) A projection optical system according to any one of Items (1) to (4) wherein said second imaging optical system includes at least one lens.

(6) A projection optical system according to Item (5) wherein said lens has a positive refracting power.

10 (7) A projection optical system according to any one of Items (1) to (6), further comprising a lens group disposed between said first and second mirrors.

(8) A projection optical system according to Item (7) wherein said lens group has a negative refracting power and wherein said lens group is disposed between said first mirror and a refractive lens of said first imaging optical system, having a positive refracting power.

15 (9) A projection optical system according to Item (1), further comprising a field optical system disposed between said first and second imaging optical systems, for projecting a pupil of said first imaging optical system onto said second imaging optical system, wherein said first imaging optical system  
20 comprises a first mirror group of positive refracting power, including at least said first mirror, and a second mirror group including said second mirror,  
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wherein light from said first mirror group as reflected by said second mirror group is caused to pass an outside of an effective diameter of said first mirror group.

5       (10) A projection optical system according to Item (9) wherein said second imaging optical system is constituted by lenses only and it has a positive refracting power.

10       (11) A projection optical system according to Item (9) or (10) wherein said second imaging optical system has a magnification BG2 which satisfies a relation  $-0.5 < BG2 < -0.05$ .

15       (12) A projection optical system according to any one of Items (9) to (11), wherein said first imaging optical system has a magnification BG1 which satisfies a relation  $-40.0 < BG1 < -0.5$ .

      (13) A projection optical system according to any one of Items (9) to (12), wherein said field optical system is all constituted by lenses.

20       (14) A projection optical system according to any one of Items (9) to (12), wherein said field optical system comprises a first field mirror and a second field mirror group including a second field mirror, wherein abaxial light passed through the outside of  
25       the effective diameter of said first mirror group is reflected by said first field mirror and said second field mirror, in this order, and after that, the light

passes a region adjacent the optical axis of said first filed mirror and enters said second imaging optical system.

5 (15) A projection optical system according to Item (14) wherein said first filed mirror comprises a concave mirror and wherein said second field mirror comprises a convex mirror.

10 (16) A projection optical system according to Item (14) wherein said first filed mirror comprises a concave mirror and wherein said second field mirror comprises a concave mirror.

15 (17) A projection optical system according to any one of Items (9) to (16), wherein relations  $P_1 < 0$  and  $P_f + P_2 > 0$  are satisfied where  $P_1$ ,  $P_f$  and  $P_2$  are Petzval sums of said first imaging optical system, said field optical system and said second imaging optical system, respectively.

20 (18) A projection optical system according to any one of Items (9) to (17), wherein a relation  $0.6 < e/LM_1 < 2.5$  is satisfied where  $LM_1$  is a paraxial distance between the object and said first mirror, and  $e$  is a distance from the object to a pupil conjugate point defined by an optical element positioned at the object side of said first mirror.

25 (19) A projection optical system according to any one of Items (9) to (18), wherein the distance  $LM_1$  satisfies a relation  $0.5 < OIL/(LM_1 + 2 \times LM_2) < 20$  where

LM2 is a paraxial distance between said first and second mirrors, and OIL is a paraxial distance along the optical path, from the object to the image defined by said first imaging optical system.

5       (20) A projection optical system according to any one of Items (9) to (19), wherein the distances LM1 and LM2 satisfy a relation  $0.2 < LM2/LM1 < 0.95$ .

10       (21) A projection optical system according to any one of Items (9) to (20), wherein the distance LM1 satisfies a relation  $0.15 < LM1/L < 0.55$  where L is a distance from an object plane to an image plane in said projection optical system.

15       (22) A projection optical system according to any one of Items (9) to (21), wherein said first mirror group has a magnification BGM1 which satisfies a relation  $-2.0 < 1/BGM1 < 0.4$ .

20       (23) A projection optical system according to any one of Items (9) to (22), wherein said first imaging optical system has a lens group of positive refracting power, disposed closest to the object side.

      (24) A projection optical system according to any one of Items (9) to (23), wherein said first mirror group includes a lens of negative refracting power and said first mirror.

25       (25) A projection optical system according to any one of Items (9) to (24), wherein said second mirror group includes said second mirror and a lens.

(26) A projection optical system according to any one of Items (9) to (25), wherein the abaxial light from the object passes a lens of said second mirror group before it is incident on said first mirror group.

(27) A projection optical system according to any one of Items (9) to (26), wherein a positive lens, included by said field optical system, is disposed just after the image plane side of said first mirror group of said first imaging optical system.

(28) A projection optical system according to any one of Items (14) to (16), wherein a relation  $0.45 < \text{LFM1}/\text{LFM2} < 0.8$  is satisfied where LFM1 is a distance between said second field mirror and said first field mirror, and LFM2 is a distance between said second field mirror and the image plane.

(29) A projection optical system according to any one of Items (14) to (16), wherein said second field mirror group includes said second field mirror and a lens.

(30) A projection optical system according to any one of Items (14) to (16), (28) and (29), wherein a positive lens, included by said field optical system, is disposed between said first mirror of said first imaging optical system and said second field mirror of said field optical system, wherein light reflected by said second mirror of said first imaging optical

system passes said positive lens and then is reflected by said first field mirror.

(31) A projection optical system according to any one of Items (1) to (30), wherein said projection  
5 optical system is telecentric with respect to each of the object side and the image plane side.

(32) A projection optical system according to any one of Items (1) to (31), wherein said projection optical system has a magnification of reduction ratio.

10 (33) A projection optical system according to any one of Items (1) to (32), further comprising a field stop disposed at the position of the image defined by said first imaging optical system, for changing at least one of a size and a shape of an imaging region  
15 upon the image plane.

(34) A projection optical system according to any one of Items (1) to (33), further comprising a stop disposed inside said second imaging optical system.

(35) A projection exposure apparatus for  
20 projecting a pattern of a mask onto a substrate through a projection optical system as recited in any one of Items (1) to (34).

(36) A projection exposure apparatus according to Item (35) wherein laser light from one of an ArF  
25 excimer laser and an F<sub>2</sub> laser is used for the projection exposure.

(37) A device manufacturing method, comprising the

steps of: printing a device pattern on a wafer by exposure, using a projection exposure apparatus as recited in item (35) or (36); and developing the exposed wafer.

5           These and other objects, features and advantages of the present invention will become more apparent upon a consideration of the following description of the preferred embodiments of the present invention taken in conjunction with the  
10           accompanying drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic view of an example of the structure of a projection optical system according to an embodiment of the present invention.  
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Figure 2 is a schematic view of an example of the structure of a projection optical system according to a first embodiment of the present invention, wherein a refractive lens group R is disposed in a group L2.  
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Figure 3 is a schematic view of a basic structure of a projection optical system according to a second embodiment of the present invention.

Figure 4 is a sectional view of a lens structure in Example 1 of the present invention.  
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Figure 5 is a sectional view of a lens structure in Example 2 of the present invention.



Figure 6 is a sectional view of a lens structure in Example 3 of the present invention.

Figure 7 is a sectional view of a lens structure in Example 4 of the present invention.

5           Figure 8 illustrates aberrations in Example 1 of the present invention.

Figure 9 illustrates aberrations in Example 2 of the present invention.

10           Figure 10 illustrates aberrations in Example 3 of the present invention.

Figure 11 illustrates aberrations in Example 4 of the present invention.

15           Figure 12 is a schematic view of a light path in a case, in Example 5 of the present invention, wherein a field optical system is all constituted by lens systems.

20           Figure 13 is a schematic view of a light path in a case, in Example 6 of the present invention, wherein a field optical system is all constituted by lens systems.

Figure 14 is a schematic view of a light path in a case, in Example 7 of the present invention, wherein a field optical system is all constituted by lens systems.

25           Figure 15 is a schematic view of a light path in a case, in Example 8 of the present invention, wherein a field optical system is all constituted by

lens systems.

Figure 16 is a schematic view of a light path  
in a case, in Example 9 of the present invention,  
wherein a field optical system is all constituted by  
5 lens systems.

Figure 17 is a schematic view of a light path  
in a case, in Example 10 of the present invention,  
wherein a field optical system is all constituted by  
lens systems.

10 Figure 18 is a schematic view of a light path  
in a case, in Example 11 of the present invention,  
wherein a field optical system is all constituted by  
lens systems.

15 Figure 19 is a schematic view of a light path  
in a case, in Example 12 of the present invention,  
wherein a field optical system is all constituted by  
lens systems.

20 Figure 20 is a schematic view of a light path  
in a case, in Example 13 of the present invention,  
wherein a field optical system includes two mirrors.

Figure 21 is a schematic view of a light path  
in a case, in Example 14 of the present invention,  
wherein a field optical system includes two mirrors.

25 Figure 22 is a schematic view of a light path  
in a case, in Example 15 of the present invention,  
wherein a field optical system includes two mirrors.

Figure 23 is a schematic view of a light path

in a case, in Example 16 of the present invention,  
wherein a field optical system includes two mirrors.

Figure 24 is a schematic view of a light path  
in a case, in Example 17 of the present invention,  
5 wherein a field optical system includes two mirrors.

Figure 25 is a schematic view of a light path  
in a case, in Example 18 of the present invention,  
wherein a field optical system includes two mirrors.

Figure 26 is a schematic view of a light path  
10 in a case, in Example 19 of the present invention,  
wherein a field optical system includes two mirrors.

Figure 27 is a schematic view of a light path  
in a case, in Example 20 of the present invention,  
wherein a field optical system includes two mirrors.

Figure 28 is a schematic view of a light path  
15 in a case, in Example 21 of the present invention,  
wherein a field optical system includes two mirrors.

Figure 29 illustrates aberrations in Example  
5 of the present invention.

Figure 30 illustrates aberrations in Example  
20 6 of the present invention.

Figure 31 illustrates aberrations in Example  
7 of the present invention.

Figure 32 illustrates aberrations in Example  
25 8 of the present invention.

Figure 33 illustrates aberrations in Example  
9 of the present invention.

Figure 34 illustrates aberrations in Example 10 of the present invention.

Figure 35 illustrates aberrations in Example 11 of the present invention.

5           Figure 36 illustrates aberrations in Example 12 of the present invention.

Figure 37 illustrates aberrations in Example 13 of the present invention.

10           Figure 38 illustrates aberrations in Example 14 of the present invention.

Figure 39 illustrates aberrations in Example 15 of the present invention.

Figure 40 illustrates aberrations in Example 16 of the present invention.

15           Figure 41 illustrates aberrations in Example 17 of the present invention.

Figure 42 illustrates aberrations in Example 18 of the present invention.

20           Figure 43 illustrates aberrations in Example 19 of the present invention.

Figure 44 illustrates aberrations in Example 20 of the present invention.

Figure 45 illustrates aberrations in Example 21 of the present invention.

25           Figure 46 illustrates numerical parameters in Examples 1 - 12 of the present invention.

Figure 47 illustrates numerical parameters in

Examples 13 - 21 of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

In accordance with an embodiment of the  
5 present invention, a catadioptric projection optical  
system, such as shown in Figure 1, is provided (First  
Embodiment). Denoted at 101 is a reticle which is  
illuminated with an illumination system, not shown.  
Denoted at 102 is a wafer, and denoted at 103 is an  
10 optical axis of an optical system in the first  
embodiment. Here, the optical system comprises at  
least first and second imaging optical systems G1 and  
G2, in an order from the object side. The reticle 101  
and the wafer 102 are held by movable stages (not  
15 shown), respectively.

The first imaging optical system G1  
comprises, in an order from the object side, at least  
a first mirror M1, having a refracting element L1, and  
and a second mirror M2. Light from the reticle 101 is  
20 imaged by the first imaging optical system G1, whereby  
an intermediate image Io is formed. Here, abaxial  
light from the reticle 101 passes an outside of the  
effective diameter of the first mirror M1. The  
intermediate image Io as imaged by the first imaging  
25 optical system G1 is then imaged on the wafer 102 by  
the second imaging optical system G2, comprising a  
refracting element, at a predetermined magnification.

In the structure described above, the optical system of the first embodiment has one optical axis 103, and it accomplishes a multiple-number imaging optical system wherein abaxial light without light interception of a pupil is imaged.

The first imaging optical system G1 comprises, at least, one or more refracting lenses and two mirrors. The refractive lens group L1 mainly functions to keep the telecentricity at the object side and contributes to correction of distortion aberration. Also, it serves so that light is incident on the first mirror M1 without excessive expansion.

The second mirror M2 is disposed opposed to the first mirror M1 and the optical axis 103, and it functions to deflect the light from the first mirror M1 toward the positive direction and also to direct the light toward the outside of the effective diameter of the first mirror M1. Here, the direction from the reticle 101 toward the wafer 102 is taken as a positive direction. With the structure described above, light can be directed to the second imaging optical system without a void in a pupil and without bend of the optical axis.

The refractive lens group L1 should desirably have a positive refracting power. With the positive refracting power, the incidence height on the first mirror M1 can be kept moderate and also the incidence

angle on the first mirror M1 with respect to the optical axis can be made large such that separation of light by the second mirror M2 is made easy. The first mirror M1 should desirably be a concave mirror.

5           In the optical system of the first embodiment, the pupil of the first imaging optical system G1 is present before or after the first mirror M1. In the portion adjacent there, the width of light at each picture angle in the first imaging optical  
10   system G1 becomes large. Additionally, dispersion of light due to the difference in picture angle becomes small. Thus, the first mirror M1 as it has a positive power, i.e., as being provided by a concave mirror, is effective to converge lights, of each picture angle,  
15   from the refractive lens group L1, such that separation of light after the second mirror M2 is made easier. Also, a curvature of field is produced in an "over" direction, thereby to cancel an "under" curvature of field in the second imaging optical  
20   system G2.

          The second mirror M2 plays a role of returning the light from the first mirror M1 toward the positive direction along the optical axis 103. Here, the second mirror M2 may be a concave mirror or  
25   a flat mirror, or a convex mirror. It should have a required shape based on the difference in power arrangement. It is to be noted that, in the first

imaging optical system G1, for cancellation of the curvature of field of the second imaging optical system G2 as well as other aberrations, the second mirror M2 may be a concave mirror. This is preferable since the refracting power of the first mirror M1 is shared by it.

The second imaging optical system G2 has a function for imaging the intermediate image Io, being imaged by the first imaging optical system G1, upon the wafer 102. The second imaging optical system G2 operates to cancel aberrations such as curvature of field in the "over" direction, for example, as produced by the first imaging optical system G1. The second imaging optical system G2 comprises a refractive lens system. By constituting a final imaging optical system with use of a refractive lens system, an optical system having a large numerical aperture can be accomplished easily.

The second imaging optical system has a reduction magnification, and this prevents an excessive increase of the width of light at the first imaging optical system G1 as well as it facilitates separation of light by the first and second mirrors M1 and M2. There is an aperture stop inside the second imaging optical system G2.

The refractive lens group R may be disposed in the group L2, including two mirrors, that is, the



first and mirrors M1 and M2.

Figure 2 is a schematic view of an example wherein a refractive lens group R is disposed in the structure of Figure 1. Here, the same reference numerals as those of Figure 1 are assigned to members having corresponding functions.

Where the refractive lens group R is disposed between the refractive lens group L1 and the first mirror M1, the structure is such as called a reciprocal optical system. Namely, into this refractive lens group R, the light refracted by the refractive lens group L1 enters and, additionally, the light reflected by the second mirror M2 passes therethrough. Where this refractive lens group R is used, the refracting power thereof should desirably be negative. If the refracting power of the refractive lens group R is negative, the Petzval sum which the first mirror M1 bears is shared. Also, it contributes to correction of chromatic aberration in the whole system. Thus, if the refractive lens group R is provided, it should desirably have a negative refracting power. Further, simultaneously, it contributes to correction of comma aberration and spherical aberration of the whole system.

As described hereinbefore, mainly for correction of axial chromatic aberration or the like, the refractive lens group R should preferably be

disposed about the first mirror M1. However, it may be disposed adjacent the second mirror R. Namely, it may be disposed at a position for transmitting the reflection light from the first mirror M1 and the reflection light from the second mirror. Further, the refractive lens group R may be disposed at any place within the range of the group L2, including two mirrors. Also, lens elements of any number may be used.

The projection optical system in this embodiment, particularly where it is provided by a twice-imaging optical system, has a positive magnification.

In the first embodiment, with the structure such as described above, a catadioptric optical system having constituent elements of a smaller number, having a high resolving power, having an assured wide exposure region, and being easy for assembling and adjustment, can be accomplished without light interception at the central portion of a pupil.

In accordance with another embodiment of the present invention, a catadioptric projection optical system such as shown in Figure 3, for example, is provided (Second Embodiment). In this embodiment, the region of the object plane from which the light reaches the image plane and which is attributable to the imaging is a semi-arcuate zone (ring-like filed)

outside the optical axis, and there is no void at the central portion of the light upon the pupil plane.

The projection optical system comprises, in an order along the optical path from the object side, a first  
5 imaging system Gr1 having a function for forming an intermediate image of the object, a field optical system Grf for projecting a pupil of the first imaging system Gr1 onto a pupil of a second imaging system Gr2, and the second imaging system Gr2 is disposed  
10 just before the image plane and operates to form a final image. The first imaging system Gr1 includes two mirror groups, i.e., a first mirror group GM1 including a first mirror M1 and having a positive refracting power, and a second mirror group GM2  
15 including a second mirror M2. The second mirror group GM2 is disposed physically at the object side of the first mirror group GM1, and the first mirror M1 is a concave mirror having its concave surface facing to the object side. The light from the object side is  
20 reflected by the first and second mirrors M1 and M2, in this order, inside the first imaging system Gr1. After this, the light goes through the outside of the effective diameter of the first mirror group GM1 toward the image side, and it passes through the field  
25 optical system Grf and the second imaging system Gr2. Thus, the whole system of the projection optical system is defined along a straight optical axis 103.

The object plane and the image plane are opposed to each other, at the opposite ends of the optical axis 103. The magnification of the projection optical system is a reduction ratio.

5           Figure 3 is a schematic view of a basic structure of the second embodiment, and Figures 12 - 45 show Examples 5 - 21, respectively, to which the second embodiment is applied, to be described later. In all examples, the first imaging system Gr1 has two  
10           mirrors, and the second imaging system Gr2 comprises refractive lens systems only. Figures 12 - 19 shows cases wherein the field optical system Grf is all provided by lens systems, and Figures 20 - 28 show cases wherein the field optical system Grf has two  
15           mirrors.

          Generally, where a mirror is used, the optical system functions as follows.

(a) No chromatic aberration occurs at the mirror.

          With this feature, when a concave lens and a  
20           concave mirror are combined to provide a Mangin mirror, even by a positive power, excessive dichromatism can be produced.

(b) The relation between the power of the mirror and the Petzval sum is opposite to that of an ordinary  
25           refractive lens.

          With this feature, since a concave mirror, for example, has a negative value of Petzval sum while

it has a positive power, the power load of a negative lens in the optical system for correction of Petzval sum can be reduced.

(c) Light rays are reflected.

5           Because of this, the optical system has to be complicated to place the object and image planes opposed to each other. For example, there occur void in the pupil, ring field, bend of optical path.

10           In this embodiment, to accomplish the above-described purposes, the functions of a mirror such as described above are effectively reflected to the optical system. As shown in Figure 3, the structure is simple and the projection optical system is disposed along a straight optical axis 103, although  
15           it uses a first imaging system, a field optical system, a second imaging system and a mirror, as shown in Figure 3. This provides significant advantages. Since there is no necessity of bending the optical path, the barrel structure can be made simple like  
20           that of a conventional refractive lens system. As regards the self-weight deformation of an optical element, since the gravity direction and the optical axis direction are registered with each other, there does not occur asymmetrical deformation. Thus, an  
25           asymmetrical aberration does not occur easily. Current equipments for manufacture such as peripheral equipments for assembling and adjustment as well as

instruments for measurement, for example, can be used. This is very advantageous in respect to the cost. Further, since the footprint of the apparatus is substantially the same as that of a conventional refractive lens system, the area to be occupied is unchanged. This feature is accomplished by the arrangement that, while an optical system concept (ring field system) in which only paraxial light contributes the imaging, is set, the function (c) described above is used twice in the first imaging system Gr1, and twice reflections are accomplished with use of two mirrors, and that the light from the object side is directed through the outside of the effective diameter of the first mirror group GM1 to the image side. The light thereafter passes through the field optical system Grf and the second imaging system Gr2, and it reaches the image plane. Thus, an optical system having a single optical axis is accomplished.

The second imaging system Gr2 is all provided by refractive lens systems, and it has a positive refracting power. With this structure, enlargement of the NA can be met and, additionally, the image side working distance can be assured easily. If the second imaging system Gr2 has a concave mirror, as described with reference to the conventional examples, it becomes difficult to enlarge the NA and to keep the

image side working distance. The field optical system Grf may be all provided by refractive lens systems, as shown at (A) in Figure 3. Alternatively, it may comprise two mirrors, such as shown at (B) in Figure 3. As will be described later in relation to examples, depending on the power arrangement, the positive lens FL1 may be omitted. In the case of (B) in Figure 3, the field optical system Grf includes a first field mirror FM1, comprising a concave mirror, and a second field mirror FM2, comprising a convex mirror. The second field mirror may be provided by a concave mirror.

As regards the color correction, the achromatic state of the first imaging system Gr1 may be made "over achromatism" on the basis of the function (a) described above, when the first mirror group GM1 is constituted by a lens LN1 of negative refracting power as well as the first mirror M1 which is a concave mirror. Thus, even though a single glass material is used for the lens, correction of chromatic aberration can be attained. This is very advantageous particularly for use of an ArF excimer laser or F<sub>2</sub> excimer laser.

As regards reduction in the number of optical elements or reduction in size and weight, since this embodiment concerns a ring field system using abaxial light only, the mirror diameter can be made smaller

than that of an optical system of a Cassegrain type or Schwarzschild type. Further, the number of mirrors is small in this embodiment, as at least two.

In the first imaging system Gr1, due to the  
5 function (b) described above, the first mirror group GM1 of the first imaging system Gr1 provides a large negative Petzval sum. Thus, the field optical system Grf and the second imaging system Gr2 can be provided, without using many negative refracting power lenses  
10 for correction of the Petzval sum as in the conventional refractive lens system. As a result, the number of lenses can be reduced. Further, where the second mirror group GM2 of the first imaging system Gr1 is provided by a lens LP1 and a mirror M2, the  
15 power sharing of the lens LP1 and the second mirror M2 can be changed, while keeping the total power of the second mirror group GM2 unchanged. Thus, the Petzval sum can be controlled as desired. The degree of freedom for aberration correction increases, and it  
20 contributes to reduction of the number of optical elements. This is also the case with the second field mirror FM2 shown at (B) in Figure 3 and, by combining the second field mirror FM2 and the lens LF into a second field mirror group, the degree of freedom for  
25 the Petzval sum correction increases, which contributes to reduction in the number of optical elements. There arises a necessity that the positive



refracting power of the second imaging system Gr2 should be made large so as to cancel the large negative Petzval sum of the first imaging system Gr1. Since the principal light ray height emitted from the first imaging system Gr1 passes the outside of the first mirror group GM1, it is incident on the field optical system Grf at a high position. Thus, the angle of the principal light ray entering the second imaging system Gr2 from the field optical system Grf becomes larger. As a result, in order to maintain the image-side telecentricity, there arises a necessity that the positive refracting power of the second imaging system Gr2 should be larger. Since the positive refracting power of the second imaging system Gr2 can be enlarged without contradiction to these two necessities, the effective diameter of the second imaging system Gr2 becomes smaller. Thus, the reduction in size and weight is accomplished.

As regards the incidence angle and reflection angle of light on the mirror, because this embodiment concerns a ring field system, the incidence angle and the reflection angle of the light on the mirror can be made smaller than that in an optical system of a Cassegrain type or Schwarzschild type. Further, in the first imaging system Gr1, the first mirror M1 is disposed adjacent a point optically conjugate with a pupil, and the light reflected by the second mirror M2

passes about the outside of the effective diameter of the first mirror group GM1. Since the light is not reflected at a high position away from the optical axis of the mirror, the incidence angle and the reflection angle of the light on the first and second mirrors M1 and M2 do not become extraordinarily large. In a case where the field optical system Grf has a structure such as shown at (B) in Figure 3, the spacing between the first and second field mirrors FM1 and FM2 is kept large as much as possible. Also, the width of light is narrow. Therefore, the incidence angle and the reflection angle do not become extraordinarily large.

As regards the width of the imaging region on the image plane, the mirror should be disposed so as to keep the effective light as much as possible. Where the field optical system Grf comprises only a refractive lens system (Figure 3, (A)) or it includes a mirror (Figure 3, (B)), in the first imaging system Gr1, the object height may be made high within the tolerable range of aberration correction. Thus, this is not an obstacle. In the field optical system Grf having a field mirror (Figure 3, (B)), since the width of light is narrow, it is easy to avoid eclipse of the effective light flux. Therefore, a sufficient imaging region width can be attained.

In the first imaging system Gr1, a positive

lens group G1 may be disposed just after the object plane. This is effective for the correction of distortion aberration, for example, and to maintain its object-side telecentricity satisfactorily.

5 Therefore, in order to reduce any warp of the object plane (reticle) or image plane (wafer) or to decrease a change in magnification due to defocus, it is desirable to provide an optical system being telecentric both in the object side and the image  
10 side, by using the positive lens group G1 and the second imaging system Gr2. In the present invention, as shown in Figure 3, the second mirror M2 should have a half disk-like shape, for separation of light. The positive lens group G1 may have either a half disk-  
15 like shape, or it may have a disk-like shape for easiness of lens manufacture and lens holding. Further, the second mirror M2 may be formed at the surface portion below the optical axis. For the same reason, the lens LP1 having a half disk-like shape,  
20 may have a disk-like shape. In that occasion, the light passes the lens LP1 three times. Similarly, the second mirror M2 may be formed at the lower surface portion of the lens LP1. Also, the first mirror M1 may be formed as a back-surface mirror of the lens  
25 LN1. The mirrors used in the present invention may be back-surface mirrors, in respect to the aberration correction.

As shown at (A) and (B) of Figure 3, the field optical system includes a positive lens FL1 disposed at the back, on the image plane side, of the first mirror group GM1 of the first imaging system Gr1. This structure suppresses enlargement of the diameter. While it is necessary to form the first face of the positive lens FL1 to have a discontinuous shape such as dual curvature, for example, the first mirror M1 may be formed at the central portion of the positive lens FL1. Further, a field stop may be disposed at the position of an intermediate image of the first imaging system, to define a variable imaging region on the image plane. This is effective to make the illumination system (not shown) very simple.

In the second embodiment, the optical system should preferably satisfy the following conditions.

Where the magnification of the second imaging system Gr2 is BG2, the following relation should be satisfied:

$$-0.5 < BG2 < -0.05 \quad \dots(1)$$

Where the magnification of the first imaging system Gr1 is BG1, the following relation should be satisfied:

$$-40.0 < BG1 < -0.5 \quad \dots(2)$$

When the Petzval sums of the first imaging system Gr1, of the field optical system Grf and of the second imaging system are P1, Pf and P2, respectively,

the following relations are satisfied:

$$P1 < 0$$

$$Pf+P2 > 0 \quad \dots(3)$$

When the paraxial distance between the object  
5 and the first mirror is LM1, and the distance from the  
object to a pupil conjugate point defined by an  
optical element, which is at the object side of the  
first mirror, is e, these distances satisfy the  
following relation:

10  $0.6 < e/LM1 < 2.5 \quad \dots(4)$

Where the paraxial distance between the first  
and second mirrors is LM2, and the paraxial distance  
from the object plane to the intermediate image by the  
first imaging system is OIL, the distance LM1  
15 described above satisfies the following relation:

$$0.5 < OIL/(LM1+2xLM2) < 20 \quad \dots(5)$$

The distances LM1 and LM2 satisfy the  
following relation:

$$0.2 < LM2/LM1 < 0.95 \quad \dots(6)$$

20 Where the distance from the object plane to  
the image plane with respect to the projection optical  
system is L, the distance LM1 described above  
satisfies the following relation:

$$0.15 < LM1/L < 0.55 \quad \dots(7)$$

25 When the magnification of the first mirror  
group is BGM1, the following relation is satisfied:

$$-2.0 < 1/BGM1 < 0.4 \quad \dots(8)$$

The condition (1) defines the magnification of the second imaging system Gr2 in a proper range, so as to obtain a good imaging performance and to assure the back focus (image side working distance), while  
5 meeting enlargement of the NA. By keeping a negative value throughout the whole range, the back focus is assured easily.

Here, if the lower limit is exceeded, the power of the second imaging system Gr2 becomes small,  
10 such that the diameter of the second imaging system becomes large, or the virtual object height with respect to the second imaging system Gr2 becomes low. As a result, the powers of the groups constituting the field optical system Grf become larger, causing  
15 difficulties in correction of distortion aberration or curvature of field. Alternatively, the magnification of the first imaging system Gr1 becomes too small, such that there may occur interference of the reflection light from the second mirror M2 with the  
20 first mirror group GM1. This makes the power arrangement difficult. On the other hand, if the upper limit is exceeded, the power of the second imaging system Gr2 increases, and it makes the correction of aberration difficult to accomplish.  
25 Further, the diameter of the field optical system Grf disadvantageously increases.

The condition (2) defines the magnification

of the first imaging system Gr1 so that, while keeping an appropriate power of the first imaging system Gr1, the reflection light from the second mirror M2 efficiently passes without interference with the first mirror group GM1. If the lower limit is exceeded, the width of light becomes large at the outside of the first mirror group GM1, to cause an enlargement of the field optical system Grf or an increase of the power of the second imaging system Gr2. This makes the aberration correction difficult to accomplish.

If the upper limit is exceeded, the power of the first imaging system Gr1 increases to cause difficulties in aberration correction. Alternatively, there may occur an inconvenience that the reflection light from the second mirror M2 interferes with the first mirror group GM1. Here, the lower limit of the condition (2) may preferably be equal to -5.0.

The condition (3) relates to the Petzval sum which determines the field curvature of the optical system as a whole. The Petzval sum of the whole system may preferably be equal to about zero. However, in this embodiment, due to the presence of the first mirror group GM1, the Petzval sum of the first imaging system Gr1 has a large negative value. In order to cancel this, the total of the Petzval sum of the field optical system Grf and that of the second imaging system Gr2 has a large positive value. If

this condition is not satisfied, for correction of the Petzval sum, the number of lenses becomes larger, or the correction of curvature of field becomes difficult to accomplish.

5           The condition (4) concerns the positional relation of the pupil conjugate point of the first imaging system and the first mirror M1. Taking into account a decrease of curvature of field or higher order distortion aberration and a decrease of the  
10 mirror incidence angle such as described above, it is desirable to take the positional relation substantially registered. If the lower limit is exceeded, the heights as the principal rays from each object height are reflected by the first mirror M1  
15 differ from each other. This causes increases of higher order distortion aberration and the curvature of field. Also, since the diameter of the first mirror group GM1 becomes larger, there occurs an inconvenience of interference of the reflection light  
20 from the second mirror M2 with the first mirror group GM1. If the upper limit is exceeded, similarly the heights as the principal rays from each object height are reflected by the first mirror M1 differ from each other, and it causes increases of higher order  
25 distortion aberration as well as the curvature of field. Also, since the angle of the reflection light from the second mirror M2 with respect to the optical



axis becomes larger, the power sharing of the field optical system Grf becomes large, which makes it difficult to accomplish the aberration correction.

Condition (5) concerns the positional  
5 relation of the intermediate image by the first  
imaging system Gr1 and the first mirror M1. Under the  
condition, the reflection light from the second mirror  
M2 efficiently passes toward the image side without  
interference with the first mirror group GM1. As  
10 shown in Figure 3, it is preferable that an  
intermediate image is formed substantially outside the  
first mirror M1. Thus, if this range is exceeded, the  
width of light outside the first mirror M1 becomes  
large, and the diameter of the field optical system  
15 Grf becomes large. This causes an increase of  
aberration. Particularly, if the lower limit is  
exceeded, the magnification of the first imaging  
system Gr1 becomes too small, and there may occur an  
inconvenience of interference of the reflection light  
20 from the second mirror M2 with the first mirror group  
GM1. Further, the powers of the first and second  
mirrors M1 and M2 become too large, and the amount of  
aberration production undesirably increases. If the  
upper limit is exceeded, to the contrary, the  
25 magnification of the first imaging system Gr1 becomes  
too large. As a result, an excessive space is  
produced outside the first mirror M1, or the

magnification has to be reduced by means of the second imaging system Gr2. Thus, the power balance of the optical system as a whole is undesirably be destroyed. The upper limit of the condition (5) may preferably be equal to 3.0.

Condition (6) defines a proper position of the second mirror M2 with respect to the first mirror M1. If the lower limit is exceeded, it causes an inconvenience that the light directed from the object plane to the first mirror M1 is eclipsed by the second mirror M2. If the upper limit is exceeded, the second mirror M2 and the object plane come close to each other, and the space at the object side becomes small.

Condition (7) defines a proper position of the first mirror M1 with respect to the total length of the optical system. If this range is exceeded, the power balance of the optical system as a whole is undesirably destroyed. Particularly, if the lower limit is exceeded, the power of the first imaging system Gr1 increases. If the upper limit is exceeded, the power of the second imaging system increases. The balance of Petzval sum or aberration cancelling relation is undesirably destroyed.

Condition (8) defines the magnification of the first mirror group GM1 in the first imaging system Gr1. If this range is exceeded, the power of the first mirror group GM1 goes beyond a proper range.

The power of the second mirror group GM2 for causing the reflection light from the second mirror M2 to pass through the outside of the first mirror group GM1, is restricted. This results in higher order aberration or curvature of field. The light may interfere with the first mirror group GM1. Further, the power balance with the second imaging system Gr2 is influenced, to cause the aberration correction more difficult. Particularly, if the lower limit is exceeded, the magnification of the first imaging system Gr1 becomes larger toward the enlargement side, so that the power of the second imaging system Gr2 becomes larger. Any way, the aberration correction is difficult to accomplish. The upper limit of the condition (8) may preferably be equal to -0.2.

Particularly, in an embodiment such as shown at (B) in Figure 3, the field optical system Grf comprises a first field mirror FM1 being a concave mirror having a concave surface facing to the object side, and a second field mirror group GFM2 including a second field mirror FM2. The first field mirror FM1 is physically disposed at the image plane side of the second field mirror group GFM2. The second imaging system Gr2 is constituted by refractive lenses only, and it has a positive refracting power. Light from the object is reflected in the first imaging system Gr1 by the first and second mirrors M1 and M2, in this

order, and after this, the light passes the outside of  
an effective diameter of the first mirror group GM1 to  
the image side. Then, the light is reflected in the  
field optical system, by the first and second field  
5 mirrors FM1 and FM2 in this order. Thereafter, the  
light goes about the optical axis center of the first  
field mirror FM1 to the image plane side, and finally  
it passes the second imaging system Gr2. Thus, the  
projection optical system as a whole is provided along  
10 a straight line of optical axis 103. The object plane  
and the image plane are opposed to each other, at the  
opposite ends of the optical axis 103. The  
magnification of the projection optical system as a  
whole is at a reduction ratio.

15 Important features of an embodiment such as  
shown at (B) in Figure 3 reside in that, in the first  
imaging system Gr1, the above-described function (c)  
are used twice such that the reflection is performed  
twice by using two mirrors of the first and second  
20 mirrors M1 and M2, and that the light from the object  
is directed through the outside of the effective  
diameter of the first mirror group GM1 to the image  
plane side. Also, even in the field optical system  
Grf, the above-described function (c) is used twice,  
25 and the reflection is made twice by using two mirrors  
of first and second field mirrors FM1 and FM2, so that  
the light is directed to the image plane side through

the optical axis central portion of the first field mirror FM1.

The optical system of this embodiment preferably satisfies the following conditions.

5           Where the magnification of the first imaging system Gr1 is BG1, the following relation should be satisfied:

$$-40.0 < BG1 < -0.9 \quad \dots(9)$$

10           When the distance between the object plane and the first mirror M1 is LM1, and the distance of a pupil conjugate point defined by an optical element, which is at the object side of the first mirror M1, is e, these distances satisfy the following relation:

$$0.8 < e/LM1 < 1.5 \quad \dots(10)$$

15           The distance LM1, the distance LM2 between the first and second mirrors M1 and M2, and the paraxial distance OIL from the object plane to the intermediate image by the first imaging system Gr1 satisfy the following relation:

20            $0.6 < OIL/(LM1+2 \times LM2) < 20 \quad \dots(11)$

          The distance LM1 and the conjugate length L of the projection optical system as a whole satisfy the following relation:

$$0.25 < LM1/L < 0.55 \quad \dots(12)$$

25           When the magnification of the first mirror group GM1 is BGM1, the following relation is satisfied:

$$-1.2 < 1/BGM1 < 0.4 \quad \dots(13)$$

The distance LFM1 between the first and second field mirrors FM1 and FM2, and the distance LFM2 between the second field mirror FM2 and the image plane, satisfy the following relation:

$$0.45 < LFM1/LFM2 < 0.8 \quad \dots(14)$$

Conditions (9) to (13) are similar to those described hereinbefore. Condition (14) defines the positional relation of the first and second field mirrors FM1 and FM2. If the lower limit is exceeded, the space between the first and second field mirrors FM1 and FM2 becomes narrower, and the powers of the mirrors become larger. Thus, the aberration at the mirror surface disadvantageously increases. If the upper limit is exceeded, the lens space for constituting the second imaging system Gr2 becomes narrower, and the aberration disadvantageously increases due to an increase of the power of each lens.

In the second embodiment of the present invention as described above, the optical system comprises a first imaging system, a field optical system and a second imaging system. Two mirrors of the first imaging system are used to perform reflection twice, to direct light to the image plane side. By this, the structure becomes very simple wherein the optical axis extends a single straight

line. Further, when predetermined conditions such as positional relations of the mirrors, and magnification sharing of each imaging system and each mirror group, are satisfied, a sufficient imaging region width is attainable. Thus, a catadioptric projection optical system which is small in size and light in weight, which has optical elements of a reduced number, which has incidence angles and reflection angles on the mirrors not being very large, and which has a sufficient image side working distance, is accomplished.

Specific example of the present invention will now be described. Examples 1 - 4 are those based on the first embodiment described above, and examples 5 - 21 are those based on the second embodiment.

[Example 1]

Figure 4 shows a specific lens structure of Example 1. The projection magnification was 1:4, and the design base wavelength was 157 nm. The glass material was fluorite.

The projection optical system comprises, in an order from the object side, a refractive lens group L1 having a positive refracting power, a refractive lens group R which is a reciprocal optical system wherein both the incidence light and reflection light of a first mirror M1 (to be placed later) transmit therethrough, a concave mirror (first mirror) M1, a

concave mirror (second mirror) M2, a field lens group F, and a second imaging optical system G2.

In this embodiment, the image side numerical aperture was  $NA = 0.6$ , the reduction magnification was 1:4, and the object-to-image distance (from the first object plane to the second object plane) was  $L =$  about 1170 mm. The design base wavelength was 157 nm. In the range of the image height of about 11.25 - 19.75 mm, the aberration was corrected. An abaxial exposure region of arcuate shape, having at least a size of about 26 mm in the lengthwise direction and 8 mm in the width was assured.

Figure 8 shows longitudinal and transverse aberrations of this example, and structural specifications of numerical example are shown in Table 1. The aberrations in the drawing concern the base wavelength 157 nm  $\pm 2$  pm.

The refractive lens group L1 comprises, in an order from the object side, an aspherical positive lens having a biconvex shape, and an aspherical positive lens of approximately flat-convex shape having a convex surface facing to the object side. With the refractive lens group L1, the telecentricity and the balance of distortion aberration are held satisfactorily and, additionally, the light is refracted toward the first mirror M1 and the reciprocal optical system R.



The refractive lens group R (reciprocal optical system) comprises an aspherical negative lens of meniscus shape, having a concave surface facing to the object side. With this negative lens, mainly the curvature of field and axial chromatic aberration are corrected. Also, with the aspherical surface, mainly the spherical aberration and comma aberration, for example, are corrected.

The first mirror M1 comprises an aspherical surface concave mirror having a concave surface facing to the object side. It has a positive refracting power and functions to produce a curvature of field in the positive direction to cancel the negative curvature of field of the second imaging optical system which comprises a refractive lens. The second mirror M2 comprises a concave mirror having a concave surface facing to the image side, and it serves to direct the abaxial light on the first object 101 to the outside of the effective diameter of the first mirror M1. An intermediate image is formed adjacent the outside of the effective diameter of the first mirror M1. In this example, the first imaging optical system is an enlarging system, and separation between the reflection light from the first mirror M1 and the reflection light from the second mirror M2 is accomplished easily.

In this example, a single aspherical lens of

biconvex shape is disposed, as a field lens group F, adjacent to the intermediate image.

The second imaging optical system G2 comprises, in an order from the object side, an  
5 aspherical positive lens of meniscus shape having a concave surface facing to the object side, an aperture stop, an aspherical positive lens of approximately flat-convex shape having a convex surface facing to the image side, an aspherical positive lens having a  
10 convex surface facing to the object side, an aspherical lens having a concave surface facing to the image side, an aspherical lens having a convex surface facing to the image side, and an aspherical positive lens having a convex surface facing to the object  
15 side. The second imaging optical system G2 provides a reduction system for imaging the light from the field lens group F onto the second object surface 102. Because the light is incident on the aperture stop with a certain angle, the effective diameter of the  
20 refractive lens about the aperture stop can be suppressed small. With this arrangement, various aberrations such as axial chromatic aberration and spherical aberration can be reduced and, additionally, they can be cancelled with various aberrations  
25 produced in the first imaging optical system. Thus, satisfactory aberration correction is accomplished in the whole system.

In this example, the second mirror M2 is a spherical mirror, and all the remaining elements have an aspherical surface. However, the refractive lenses of the first and second imaging optical systems G1 and G2 and the first mirror M1 may not be defined by an aspherical surface. A spherical lens or spherical mirror may be used therefor. However, use of an aspherical surface can correct the aberrations better. [Example 2]

Figure 5 shows a specific lens structure of Example 2. The projection magnification was 1:4, and the design base wavelength was 157 nm. The glass material was fluorite.

The projection optical system comprises, in an order from the object side, a refractive lens group L1 having a positive refracting power, a refractive lens group R which is a reciprocal optical system wherein both the incidence light and reflection light of a first mirror M1 (to be placed later) transmit therethrough, a concave mirror (first mirror) M1, a flat mirror (second mirror) M2, a field lens group F, and a second imaging optical system G2.

In this embodiment, the image side numerical aperture was  $NA = 0.60$ , the reduction magnification was 1:4, and the object-to-image distance (from the first object plane to the second object plane) was  $L =$  about 1205 mm. In the range of the image height of

about 10 - 16.25 mm, the aberration was corrected. An abaxial exposure region of arcuate shape, having at least a size of about 26 mm in the lengthwise direction and 4 mm in the width was assured.

5           Figure 9 shows longitudinal and transverse aberrations of this example, and structural specifications of numerical example is shown in Table 2. The aberrations in the drawing concern the base wavelength and a wavelength  $\pm 2$  pm.

10           The refractive lens group L1 comprises, in an order from the object side, a single aspherical positive lens having a biconvex shape. The group Le including two mirrors comprises a refractive lens group R (reciprocal optical system) and first and  
15           second mirrors M1 and M2.

            The refractive lens group R (reciprocal optical system) comprises an aspherical negative lens having a concave surface facing to the object side. The first mirror M1 comprises an aspherical surface  
20           concave mirror having a concave surface facing to the object side. The second mirror M2 is a flat mirror.

            A field lens group F is disposed adjacent to an intermediate image as formed by the first imaging optical system. The field lens group F comprises, in  
25           an order from the object side, an aspherical positive lens of biconvex shape, and an aspherical positive lens of meniscus shape having a concave surface facing

to the image side.

The second imaging optical system G2 comprises, in an order from the object side, an aspherical negative lens of meniscus shape having a concave surface facing to the image side, an aperture stop, an aspherical positive lens of biconvex shape, a spherical positive lens of meniscus shape having a convex surface facing to the object side, an aspherical positive lens having a convex surface facing to the image side, an aspherical positive lens having a convex surface facing to the image side, and an aspherical positive lens of approximately flat-convex shape having a convex surface facing to the object side. In this example, the second imaging optical system G2 includes a strong negative lens.

[Example 3]

Figure 6 shows a specific lens structure of Example 3. The projection magnification was 1:4, and the design base wavelength was 157 nm. The glass material was fluorite.

In this embodiment, the image side numerical aperture was  $NA = 0.68$ , the reduction magnification was 1:4, and the object-to-image distance (from the first object plane to the second object plane) was  $L =$  about 1185 mm. In the range of the image height of about 11.25 - 20.25 mm, the aberration was corrected. An abaxial exposure region of arcuate shape, having at

least a size of about 26 mm in the lengthwise direction and 8 mm in the width was assured.

Figure 10 shows longitudinal and transverse aberrations of this example, and structural specifications of numerical example is shown in Table 3. The aberrations in the drawing concern the base wavelength 157 nm  $\pm$  2 pm.

The refractive lens group L1 comprises, in an order from the object side, an aspherical positive lens of meniscus shape having a concave surface facing to the object side, and an aspherical positive lens of biconvex shape. The refractive lens group R (reciprocal optical system) comprises an aspherical negative lens of meniscus shape, having a concave surface facing to the object side.

The first mirror M1 comprises an aspherical surface concave mirror having a concave surface facing to the object side. It has a positive refracting power and functions to produce a curvature of field in the positive direction to cancel the negative curvature of field of the second imaging optical system which comprises a refractive lens. The second mirror M2 comprises an aspherical surface concave mirror having a concave surface facing to the image side, and it serves to direct the abaxial light on the first object 101 to the outside of the effective diameter of the first mirror M1. An intermediate

image is formed adjacent the outside of the effective diameter of the first mirror M1. In this example, a field lens group F is disposed adjacent to the intermediate image. This field lens group F comprises, in an order from the object side, an aspherical positive lens of meniscus shape having a convex surface facing to the image side, and an aspherical positive lens of biconvex shape.

The second imaging optical system G2 comprises, in an order from the object side, an aspherical positive lens of meniscus shape having a convex surface facing to the object side, an aperture stop, an aspherical positive lens of approximately flat-convex shape having a convex surface facing to the image side, an aspherical positive lens having a convex surface facing to the object side, an aspherical lens having a concave surface facing to the image side, an aspherical lens having a convex surface facing to the image side, and an aspherical positive lens having a convex surface facing to the object side. The second imaging optical system G2 provides a reduction system for imaging the light from the field lens group F onto the second object surface 102. Because the light is incident on the aperture stop with a certain angle, the effective diameter of the refractive lens about the aperture stop can be suppressed small. With this arrangement, various

aberrations such as axial chromatic aberration and spherical aberration can be reduced and, additionally, they can be cancelled with various aberrations produced in the first imaging optical system. Thus, satisfactory aberration correction is accomplished in the whole system.

[Example 4]

Figure 7 shows a specific lens structure of Example 4. The projection magnification was 1:5, and the design base wavelength was 157 nm (wavelength of F<sub>2</sub> excimer laser). The glass material was fluorite.

In this embodiment, the image side numerical aperture was NA = 0.60, and the object-to-image distance (from the first object plane to the second object plane) was L = about 1411 mm. In the range of the image height of about 9 - 15 mm, the aberration was corrected. An abaxial exposure region of arcuate shape, having at least a size of about 20.8 mm in the lengthwise direction and 5 mm in the width was assured.

Figure 11 shows longitudinal and transverse aberrations of this example, and structural specifications of numerical example are shown in Table 4.

The projection optical system comprises, in an order from the object side, a refractive lens group L1 having a positive refracting power, a concave



mirror (first mirror) M1, a concave mirror (second mirror) M2, and a second imaging optical system G2. In this example, there is no refractive lens group R or field lens group F, inside the group L2 having two mirrors.

The refractive lens group L1 comprises, in an order from the object side, an aspherical positive lens having a convex surface facing to the image side, and an aspherical positive lens of biconvex shape.

The first mirror M1 comprises an aspherical surface concave mirror having a concave surface facing to the object side. The second mirror M2 comprises an aspherical surface concave mirror having a concave surface facing to the image side, and it serves to direct the abaxial light on the first object 101 to the outside of the effective diameter of the first mirror M1. An intermediate image is formed adjacent the outside of the effective diameter of the first mirror M1. In this example, the first imaging optical system G1 constitutes a reduction system.

The second imaging optical system G2 comprises, in an order from the object side, an aspherical positive lens of biconvex shape, an aperture stop, two aspherical positive lenses of meniscus shape having a concave surface facing to the image side, and an aspherical positive lens having a convex surface facing to the object side. The second

imaging optical system G2 provides a reduction system for imaging the light from the second mirror M2 upon the second object surface 102.

In the four examples described above, except  
5 Example 2, the first mirror M1 is all defined by an aspherical surface. However, it may be a spherical surface. Further, except Examples 1 and 2, all the refractive lenses are aspherical lenses. However, a spherical lens may be used in combination.

10 As regards the aspherical lenses, although the surface opposite to the aspherical surface is spherical, it may be flat or spherical. Further, the first mirror or the second mirror may be provided by an aspherical surface having no refracting power.

15 In Examples 1 - 4 described above, the exposure region has an arcuate shape. However, as long as inside the aberration-corrected range, any other shape such as a rectangular shape may be used. Further, while the group L2 having two mirrors is  
20 shown as including the refractive lens group R, the refractive lens group R and the mirrors may be integrated (Mangin mirror structure). Alternatively, the refractive lens group R and the second mirror M2 may be integrated into a Mangin mirror structure.

25 In the examples described above, while there is an aspherical surface data in which the conical constant  $k$  is taken as zero, the design may be made

while using the conical constant as a variable.

The exposure light source used an  $F_2$  laser of a wavelength 157 nm. However, a KrF excimer laser (wavelength 248 nm) or ArF excimer laser (wavelength 193 nm), for example, may be used. Particularly, the invention is effective where the wavelength is shortened and usable optical materials are limited, and the number of optical elements should be reduced. Thus, the present invention is effective to an optical system to be used with a wavelength not longer than 250 nm.

In these examples, fluorite was used as the glass material for the wavelength 157 nm from the  $F_2$  excimer laser. However, any other glass material such as fluorine doped quartz, for example, may be used. Where a KrF or ArF light source is used, fluorite and quartz may be used in combination, or only one of them may be used.

[Example 5]

Figure 12 is an optical path view of Example 5 of the present invention. The design base wavelength was 157 nm of  $F_2$  excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:6. The lens conjugate distance  $L$  was 1005 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 8.64 mm to 14.40 mm. The optical system

was provided by a small number of optical elements,  
i.e., two mirrors and nine lenses.

In this example, denoted at  $r_1 - r_2$  are  
components of a first imaging system  $Gr_1$ , and it  
5 comprises a first mirror  $M_1$  (concave surface) and a  
second mirror  $M_2$  (concave surface). Denoted at  $r_3 -$   
 $r_8$  are components of a field optical system  $Gr_f$ , and  
it comprises two positive lenses, including a positive  
lens  $FL_1$  disposed at the image side of the first  
10 mirror  $M_1$ , and one negative lens. Denoted at  $r_9 - r_{21}$   
are components of a second imaging system  $Gr_2$ , and it  
comprises a stop  $r_{11}$ , four positive lenses and two  
negative lenses.

In this example, the magnification of the  
15 first imaging system  $Gr_1$  is at the most reduction rate  
and, therefore, a value close to the upper limit of  
condition (2) is taken.

Structural specifications of numerical  
examples are shown in Table 5. In this example, an  
20 image side working distance of 30 mm is assured, and  
the total glass material length along the optical path  
is extraordinarily shortened to 224.7 mm. While the  
largest diameter of the optical system as a whole is  
227 mm at the field optical system, the largest  
25 diameter of the second imaging system is small as 125  
mm, regardless of that the NA is 0.6. Figure 29 shows  
aberrations, and from this, it is seen that

aberrations are corrected satisfactorily.

[Example 6]

Figure 13 is an optical path view of Example 6 of the present invention. The design base wavelength was 157 nm of F<sub>2</sub> excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:5. The lens conjugate distance L was 956 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 7.2 mm to 14.40 mm. The optical system was provided by a small number of optical elements, i.e., two mirrors and ten lenses.

In this example, denoted at r1 - r4 are components of a first imaging system Gr1, and it comprises a positive lens (group G1) at r1 and r2, a first mirror M1 (concave surface) and a second mirror M2 (concave surface). Denoted at r5 - r10 are components of a field optical system Grf, and it comprises two positive lenses, including a positive lens FL1 disposed at the image side of the first mirror M1, and one negative lens. Denoted at r11 - r23 are components of a second imaging system Gr2, and it comprises a stop r13, four positive lenses and two negative lenses.

In this example, the magnification of the first imaging system Gr1 is at a smaller rate and, therefore, a value close to the lower limit of

condition (8) is taken. Further, based on this, the intermediate image at a paraxial portion of the first imaging system Gr1 is formed at a position after the light is reflected by the first mirror M1 and before it is incident on the second mirror M2. Therefore, a value close to the lower limit of condition (5) is taken.

Structural specifications of numerical examples are shown in Table 6. In this example, an image side working distance of 31 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 232.1 mm. While the largest diameter of the optical system as a whole is 196 mm at the field optical system, the largest diameter of the second imaging system is small as 143 mm, regardless of that the NA is 0.6. Figure 30 shows aberrations, and from this, it is seen that aberrations are corrected satisfactorily.

[Example 7]

Figure 14 is an optical path view of Example 5 of the present invention. The design base wavelength was 157 nm of F<sub>2</sub> excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:5. The lens conjugate distance L was 1199 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 8.4 mm to 14.0 mm. The optical system was

provided by a small number of optical elements, i.e., two mirrors and nine lenses.

In this example, denoted at  $r_1 - r_4$  are components of a first imaging system  $Gr_1$ , and it comprises a positive lens (group  $G_1$ ) at  $r_1$  and  $r_2$ , a first mirror  $M_1$  (concave surface) and a second mirror  $M_2$  (concave surface). Denoted at  $r_5 - r_{12}$  are components of a field optical system  $Gr_f$ , and it comprises three positive lenses, including a positive lens  $FL_1$  disposed at the image side of the first mirror  $M_1$ , and one negative lens. Denoted at  $r_{13} - r_{21}$  are components of a second imaging system  $Gr_2$ , and it comprises a stop  $r_{13}$  and four positive lenses.

In this example, since the position of a pupil conjugate point of the first imaging system  $Gr_1$  is largely remote, in the positive direction, from the position of the first mirror  $M_1$ , a value close to the upper limit of condition (4) is taken. Further, since the distance from the object plane to the first mirror  $M_1$  is short as compared with the whole optical length, a value close to the lower limit of condition (7) is taken.

Structural specifications of numerical examples are shown in Table 7. In this example, an image side working distance of 31 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 333.8 mm. While the

largest diameter of the optical system as a whole is 250 mm at the field optical system, the largest diameter of the second imaging system is small as 143 mm, regardless of that the NA is 0.6. Figure 31 shows aberrations, and from this, it is seen that aberrations are corrected satisfactorily.

[Example 8]

Figure 15 is an optical path view of Example 8 of the present invention. The design base wavelength was 157 nm of F<sub>2</sub> excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:5. The lens conjugate distance L was 1198 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 8.4 mm to 14.0 mm. The optical system was provided by a small number of optical elements, i.e., two mirrors and ten lenses.

In this example, denoted at r1 - r10 are components of a first imaging system Gr1, and it comprises a positive lens (group G1), a first mirror M1 (concave mirror) and a second mirror (concave mirror) M2. The imaging system group G1 comprises a positive lens at r1 and r2, negative lenses at r3 and r4; r6 and r7; and r9 and r10a of the same type which are physically disposed between the first and second mirrors M1 and M2. Denoted at r11 - r18 are components of a field optical system Grf, and it



comprises three positive lenses, including a positive lens FL1 disposed at the image side of the first mirror M1, and one negative lens. Denoted at r19 - r27 are components of a second imaging system Gr2, and it comprises a stop r19 and four positive lenses.

In this example, the negative lenses are provided in the first imaging system Gr1, between the first mirror M1 and the second concave mirror M2, so as to avoid the inconvenience of interference of the reflection light from the second mirror with the first mirror M1 and also to correct distortion aberration, for example.

Structural specifications of numerical examples are shown in Table 8. In this example, an image side working distance of 36.1 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 337.6 mm. While the largest diameter of the optical system as a whole is 245 mm at the field optical system, the largest diameter of the second imaging system is small as 142 mm, regardless of that the NA is 0.6. Figure 32 shows aberrations, and from this, it is seen that aberrations are corrected satisfactorily.

[Example 9]

Figure 16 is an optical path view of Example 9 of the present invention. The design base wavelength was 157 nm of F<sub>2</sub> excimer laser light, the

NA was 0.6, and the projection magnification  $\beta$  was 1:5. The lens conjugate distance  $L$  was 1166 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 7.7 mm to 14.0 mm. The optical system was provided by a small number of optical elements, i.e., two mirrors and twelve lenses.

In this example, denoted at  $r1 - r14$  are components of a first imaging system  $Gr1$ , and it comprises a positive lens (group  $G1$ ) at  $r1$  and  $r2$ , and positive lenses  $LP1$  at  $r3$  and  $r4$ ;  $r10$  and  $r11$ ; and  $r13$  and  $r14$  of the same type which constitute a second mirror group  $GM2$  in combination with a second mirror  $M2$ . Also, it comprises negative lenses  $LN1$  at  $r5$  and  $r6$ ; and  $r8$  and  $r9$  of the same type, for constituting a first mirror group  $GM1$  in combination with a first mirror  $M1$ .

Denoted at  $r15 - r22$  are components of a field optical system  $Grf$ , and it comprises three positive lenses, including a positive lens  $FL1$  disposed at the image side of the first mirror  $M1$ , and one negative lens. Denoted at  $r23 - r33$  are components of a second imaging system  $Gr2$ , and it comprises a stop  $r27$ , four positive lenses and one negative lens.

In this example, the position of the intermediate image formed by the first imaging system

Gr1 is substantially coincident with the position of the first mirror M1, and the intermediate image is formed outside the first mirror group GM1. Therefore, undesirable interference between the light and the first mirror group GM1 can be avoided easily. Further, the structure is efficient since enlargement of the diameter of the field optical system can be suppressed. The second mirror group GM2 is provided by the positive lens LP1 and the second mirror M2, to thereby control the Petzval sum. On the other hand, since the imaging state of the intermediate image is moderate, a field stop may be provided at that position.

Structural specifications of numerical examples are shown in Table 9. In this example, an image side working distance of 30.3 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 400.5 mm. While the largest diameter of the optical system as a whole is 213 mm at the field optical system, the largest diameter of the second imaging system is small as 157 mm, regardless of that the NA is 0.6. Figure 33 shows aberrations, and from this, it is seen that aberrations are corrected satisfactorily.

[Example 10]

Figure 17 is an optical path view of Example 10 of the present invention. The design base

wavelength was 157 nm of  $F_2$  excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:5. The lens conjugate distance  $L$  was 1160 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 7.7 mm to 14.0 mm. The optical system was provided by a small number of optical elements, i.e., two mirrors and twelve lenses.

In this example, denoted at  $r1 - r14$  are components of a first imaging system  $Gr1$ , and it comprises a positive lens (group  $G1$ ) at  $r1$  and  $r2$ , and positive lenses  $LP1$  at  $r3$  and  $r4$ ;  $r10$  and  $r11$ ; and  $r13$  and  $r14$  of the same type which constitute a second mirror group  $GM2$  in combination with a second mirror  $M2$ . Also, it comprises negative lenses  $LN1$  at  $r5$  and  $r6$ ; and  $r8$  and  $r9$  of the same type, for constituting a first mirror group  $GM1$  in combination with a first mirror  $M1$ .

Denoted at  $r15 - r22$  are components of a field optical system  $Grf$ , and it comprises three positive lenses, including a positive lens  $FL1$  disposed at the image side of the first mirror  $M1$ , and one negative lens. Denoted at  $r23 - r33$  are components of a second imaging system  $Gr2$ , and it comprises a stop  $r27$ , four positive lenses and one negative lens.

In this example, particularly, the first

mirror group GM1 of the first imaging system Gr1 is provided by the negative lens LN1 and the first mirror M1, and the power of each element is strengthened. By this, the effect of correcting chromatic aberration with respect to the whole optical system is enhanced. Further, the second mirror group GM2 is provided by the positive lens LP1 and the second mirror M2, to thereby control the Petzval sum.

Structural specifications of numerical examples are shown in Table 10. In this example, an image side working distance of 30.0 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 375.9 mm. While the largest diameter of the optical system as a whole is 266 mm at the field optical system, the largest diameter of the second imaging system is small as 105 mm, regardless of that the NA is 0.6. Figure 34 shows aberrations with respect to the base wavelength 157 nm and a wavelength range of 2 nm. From the drawing, it is seen that aberrations are corrected satisfactorily. [Example 11]

Figure 18 is an optical path view of Example 11 of the present invention. The design base wavelength was 157 nm of  $F_2$  excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:4. The lens conjugate distance  $L$  was 1430 mm. The optical system had an exposure region (imaging region)

upon an image plane, of an arcuate shape, at the image height from 8.19 mm to 13.65 mm. The optical system was provided by a small number of optical elements, i.e., two mirrors and twelve lenses.

5           In this example, denoted at r1 - r12 are components of a first imaging system Gr1, and it comprises a positive lens (group G1) at r1 and r2, and negative lenses LN1 at r3 and r4; and r6 and r7 of the same type which constitute a first mirror group GM1 in  
10 combination with a first mirror M1. Also, it comprises positive lenses LP1 at r8 and r9; and r11 and r12 of the same type, for constituting a second mirror group GM2 in combination with a second mirror M2.

15           Denoted at r13 - r20 are components of a field optical system Grf, and it comprises three positive lenses, including a positive lens FL1 disposed at the image side of the first mirror M1, and one negative lens. Denoted at r21 - r31 are  
20 components of a second imaging system Gr2, and it comprises a stop r25, four positive lenses and one negative lens.

          In this example, like Example 10, due to the structure of the first mirror group GM1 as described,  
25 the effect of correcting chromatic aberration is enhanced. Further, the second mirror group GM2 is provided by the positive lens LP1 and the second

mirror M2, to thereby control the Petzval sum.

Structural specifications of numerical examples are shown in Table 11. In this example, an image side working distance of 30.0 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 371.9 mm. While the largest diameter of the optical system as a whole is 328 mm at the field optical system, the largest diameter of the second imaging system is small as 141 mm, regardless of that the NA is 0.6. Figure 35 shows aberrations with respect to the base wavelength 157 nm and a wavelength range of 2 nm. From the drawing, it is seen that aberrations are corrected satisfactorily. [Example 12]

Figure 19 is an optical path view of Example 12 of the present invention. The design base wavelength was 157 nm of  $F_2$  excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:4. The lens conjugate distance L was 1430 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 8.19 mm to 13.65 mm. The optical system was provided by a small number of optical elements, i.e., two mirrors and twelve lenses, like Example 11.

In this example, denoted at r1 - r12 are components of a first imaging system Gr1, and it comprises a positive lens (group G1) at r1 and r2, and

negative lenses LN1 at r3 and r4; and r6 and r7 of the same type which constitute a first mirror group GM1 in combination with a first mirror M1. Also, it comprises positive lenses LP1 at r8 and r9; and r11 and r12 of the same type, for constituting a second mirror group GM2 in combination with a second mirror M2. In Figure 20, the positive lens group G1 as well as the positive lens LP1 are of half disk-like shape.

Denoted at r13 - r20 are components of a field optical system Grf, and it comprises three positive lenses, including a positive lens FL1 of doughnut shape, having a hollow at its center, and being disposed outside the first mirror M1, and one negative lens. Denoted at r21 - r31 are components of a second imaging system Gr2, and it comprises a stop r25, four positive lenses and one negative lens.

In this example, since the pupil conjugate point of the first imaging system Gr1 is placed closer to the object side, a value close to the lower limit of condition (4) is taken. Further, like Example 10, due to the structure of the first mirror group GM1 as described, the effect of correcting chromatic aberration is enhanced. Also, the positive lens FL1 of the field optical system Grf is made into a doughnut shape, and the first mirror group GM1 of the first imaging system Gr1 is disposed at the central portion of the doughnut shape. With this structure,



the light rays can be refracted at a position closer to the object side and, therefore, the powers of the field optical system Grf and the second imaging system Gr2 can be made smaller. This is very advantageous in respect to the aberration correction. Further, the second mirror group GM2 is provided by the positive lens LP1 and the second mirror M2, to thereby control the Petzval sum.

Structural specifications of numerical examples are shown in Table 12. In this example, an image side working distance of 30.0 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 377.0 mm. While the largest diameter of the optical system as a whole is 328 mm at the field optical system, the largest diameter of the second imaging system is small as 144 mm, regardless of that the NA is 0.6. Figure 36 shows aberrations with respect to the base wavelength 157 nm and a wavelength range of 2 nm. From the drawing, it is seen that aberrations are corrected satisfactorily. [Example 13]

Figure 20 is an optical path view of Example 13 of the present invention. The design base wavelength was 157 nm of F<sub>2</sub> excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:5. The lens conjugate distance L was 1100 mm. The optical system had an exposure region (imaging region)

upon an image plane, of an arcuate shape, at the image height from 10.24 mm to 13.65 mm. The optical system was provided by an extraordinarily simple structure, i.e., with four mirrors and five lenses.

5           In this example, denoted at  $r_1 - r_2$  are components of a first imaging system  $Gr_1$ , and it comprises a first mirror  $M_1$  (concave surface) and a second mirror  $M_2$  (concave surface), only. Denoted at  $r_3 - r_4$  are components of a field optical system  $Gr_f$ ,  
10 and it comprises a first field mirror  $FM_1$  (concave surface) and a second field mirror  $FM_2$  (convex surface), only. Denoted at  $r_5 - r_{15}$  are components of a second imaging system  $Gr_2$ , and it comprises a stop  $r_5$ , four positive lenses and one negative lens.

15           In this example, the first mirror  $M_1$  is positioned relatively at the object side, with respect to the conjugate distance of the whole optical system, and therefore a value close to the lower limit of condition (12) is taken.

20           Structural specifications of numerical examples are shown in Table 22. In this example, an image side working distance of 30.0 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 192.2 mm. While the  
25 largest diameter of the optical system as a whole is 388 mm at the field optical system, the largest diameter of the second imaging system is small as 167

mm, regardless of that the NA is 0.6. Figure 37 shows aberrations. From the drawing, it is seen that aberrations are corrected satisfactorily.

[Example 14]

5           Figure 21 is an optical path view of Example 14 of the present invention. The design base wavelength was 157 nm of F<sub>2</sub> excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:5. The lens conjugate distance L was 1100 mm. The  
10           optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 10.24 mm to 13.65 mm. The optical system was provided by a simple structure, i.e., with four mirrors and six lenses (one lens added to Example 13).

15           In this example, denoted at r1 - r2 are components of a first imaging system Gr1, and it comprises a first mirror M1 (concave surface) and a second mirror M2 (concave surface which is very close to a flat surface), only. Denoted at r3 - r8 are  
20           components of a field optical system Grf, and it comprises a first field mirror FM1 (concave surface), a second field mirror FM2 (convex surface), and negative lenses LF at r4 and r5; and r7 and r8 of the same type. Denoted at r9 - r19 are components of a  
25           second imaging system Gr2, and it comprises a stop r9, four positive lenses and one negative lens.

          In this example, with use of the second field

mirror group GFM2 which is provided by the second field mirror FM2 (concave) and the negative lens LF, the Petzval sum is also controlled. Further, the magnification of the second imaging system Gr2 is made small, such that a value close to the upper limit of condition (1) is taken. Since the first imaging system Gr1 does not include the positive lens group G1, the second mirror M2 is positioned closer to the object side. Therefore, a value close to the upper limit of condition (6) is taken.

Structural specifications of numerical examples are shown in Table 14. In this example, an image side working distance of 30 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 156.4 mm. While the largest diameter of the optical system as a whole is 444 mm at the field optical system, the largest diameter of the second imaging system is small as 144 mm, regardless of that the NA is 0.6. Figure 38 shows aberrations. From the drawing, it is seen that aberrations are corrected satisfactorily.

[Example 15]

Figure 22 is an optical path view of Example 15 of the present invention. The design base wavelength was 157 nm of F<sub>2</sub> excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:4. The lens conjugate distance L was 1190 mm. The

optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 9.56m to 13.65 mm. The optical system was provided by use of four mirrors and eight lenses (two  
5 lens added to Example 13).

In this example, denoted at r1 - r8 are components of a first imaging system Gr1, and it comprises a positive lens (G1) at r1 and r2, negative lenses LN1 at r3 and r4; and r6 and r7 of the same  
10 type, a first mirror M1 (concave surface) and a second mirror M2 (convex surface). Denoted at r9 - r14 are components of a field optical system Grf, and it comprises a first field mirror FM1 (concave surface), a second field mirror FM2 (convex surface), and  
15 positive lenses LF at r10 and r11; and r13 and r14 of the same type. Denoted at r15 - r25 are components of a second imaging system Gr2, and it comprises a stop r15, four positive lenses and one negative lens.

In this example, the convex lens group G1 is  
20 provided in the first imaging system Gr1, by which the optical system is made telecentric on the object side. Also, the first mirror group GM1 is provided by the negative lens LN1 and the first mirror M1, by which color correction is performed. Further, with use of  
25 the second field mirror group GFM2 which is provided by the second field mirror FM2 (convex) and the positive lens LF, the Petzval sum is also controlled.

Further, since the pupil conjugate point of the first imaging system Grl is closer to the object side, a value close to the lower limit of condition (10) is taken. Also, since the spacing between the second and first field mirrors FM2 and FM1 is relatively large, a value close to the upper limit of condition (14) is taken.

Structural specifications of numerical examples are shown in Table 15. In this example, an image side working distance of 36 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 203.7 mm. While the largest diameter of the optical system as a whole is 512 mm at the field optical system, the largest diameter of the second imaging system is small as 146 mm, regardless of that the NA is 0.6. Figure 39 shows aberrations with respect to the base wavelength 157 nm and a wavelength range of 4 nm. From the drawing, it is seen that aberrations are corrected satisfactorily.

[Example 16]

Figure 23 is an optical path view of Example 16 of the present invention. The design base wavelength was 157 nm of F<sub>2</sub> excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:5. The lens conjugate distance L was 1190 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image

height from 9.56m to 13.65 mm. The optical system was provided by use of four mirrors and nine lenses (one lens added to Example 15).

In this example, denoted at r1 - r8 are components of a first imaging system Gr1, and it comprises a positive lens (G1) at r1 and r2, negative lenses LN1 at r3 and r4; and r6 and r7 of the same type, a first mirror M1 (concave surface) and a second mirror M2 (convex surface). Denoted at r9 - r16 are components of a field optical system Grf, and it comprises a positive lens FL1, a first field mirror FM1 (concave surface), a second field mirror FM2 (convex surface), and negative lenses LF at r12 and r13; and r15 and r16 of the same type. Denoted at r17 - r27 are components of a second imaging system Gr2, and it comprises a stop r17, four positive lenses and one negative lens.

In this example, the magnification of the first imaging system Gr1 is slightly enlarged to - 3.838x and, in consideration of it, the positive lens FL1 included in the field optical system Grf is disposed at the back, on the image side, of the first mirror M1 to thereby suppress the increase of diameter. Further, with use of the first mirror group GM1 including the negative lens LN1 and the first mirror M1, as well as the second field mirror group GFM2 which is provided by the second field mirror FM2

(convex) and the negative lens LF, the Petzval sum is also controlled.

Structural specifications of numerical examples are shown in Table 16. In this example, an image side working distance of 36 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 292.8 mm. While the largest diameter of the optical system as a whole is 294 mm at the field optical system, the largest diameter of the second imaging system is small as 184 mm, regardless of that the NA is 0.6. Figure 40 shows aberrations. From the drawing, it is seen that aberrations are corrected satisfactorily.

[Example 17]

Figure 24 is an optical path view of Example 17 of the present invention. The design base wavelength was 157 nm of F<sub>2</sub> excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:4. The lens conjugate distance L was 1188 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 9.56 mm to 13.65 mm. The optical system was provided by use of four mirrors and nine lenses.

In this example, denoted at r1 - r8 are components of a first imaging system Gr1, and it comprises a positive lens (G1) at r1 and r2, negative lenses LN1 at r3 and r4; and r6 and r7 of the same



type, a first mirror M1 (concave surface) and a second  
mirror M2 (convex surface). Denoted at r9 - r16 are  
components of a field optical system Grf, and it  
comprises a positive lens FL1, a first field mirror  
5 FM1 (concave surface), a second field mirror FM2  
(concave surface), and positive lenses LF at r12 and  
r13; and r15 and r16 of the same type. Denoted at r17  
- r27 are components of a second imaging system Gr2,  
and it comprises a stop r17, four positive lenses and  
10 one negative lens.

In this example, the second field mirror FM2  
as well as the positive lens LF, at the back thereof,  
are provided in the field optical system Grf. With  
this structure, an intermediate image is formed also  
15 just after (image side) of the positive lens LF.  
Thus, in the whole optical system, the imaging is  
executed three times. Therefore, after the field  
optical system Grf, the positive power becomes larger  
and the space is made smaller. Thus, the position of  
20 the first mirror M1 is placed relatively at the image  
side, and a value close to the upper limit of  
condition (12) is taken. Further, since the  
magnification at the first mirror M1 is made smaller,  
a value close to the lower limit of condition (13) is  
25 taken. As a result, the paraxial intermediate image  
at the first imaging system Gr1 is produced after the  
light which is reflected by the second mirror M2 and

at a position closer to the object side. Thus, a value close to the lower limit of condition (11) is taken. Additionally, with use of the first mirror group GM1 provided by the negative lens LN1 and the first mirror M1, color correction is made.

Structural specifications of numerical examples are shown in Table 17. In this example, an image side working distance of 36 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 303.3 mm. While the largest diameter of the optical system as a whole is 323 mm at the field optical system, the largest diameter of the second imaging system is small as 125 mm, regardless of that the NA is 0.6. Figure 41 shows aberrations, with respect to the base wavelength 157 nm and a wavelength rang of 2 pm. From the drawing, it is seen that aberrations are corrected satisfactorily.

[Example 18]

Figure 25 is an optical path view of Example 18 of the present invention. The design base wavelength was 157 nm of F<sub>2</sub> excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:4. The lens conjugate distance L was 1190 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 10.0 mm to 20.0 mm. The optical system

was provided by use of four mirrors and nine lenses,  
like Example 16.

In this example, denoted at  $r_1 - r_8$  are  
components of a first imaging system  $Gr_1$ , and it  
5 comprises a positive lens ( $G_1$ ) at  $r_1$  and  $r_2$ , negative  
lenses  $LN_1$  at  $r_3$  and  $r_4$ ; and  $r_6$  and  $r_7$  of the same  
type, a first mirror  $M_1$  (concave surface) and a second  
mirror  $M_2$  (convex surface). Denoted at  $r_9 - r_{16}$  are  
components of a field optical system  $Gr_f$ , and it  
10 comprises a positive lens  $FL_1$ , a first field mirror  
 $FM_1$  (concave surface), a second field mirror  $FM_2$   
(convex surface), and positive lenses  $LF$  at  $r_{12}$  and  
 $r_{13}$ ; and  $r_{15}$  and  $r_{16}$  of the same type. Denoted at  $r_{17}$   
-  $r_{27}$  are components of a second imaging system  $Gr_2$ ,  
15 and it comprises a stop  $r_{17}$ , four positive lenses and  
one negative lens.

In this example, with use of the first mirror  
group  $GM_1$  as provided by the negative lens  $LN_1$  and the  
first mirror  $M_1$ , color correction is accomplished.  
20 Further, with use of the second field mirror group  
 $GFM_2$  which is provided by the second field mirror  $FM_2$   
(convex) and the positive lens  $LF$ , the Petzval sum is  
also controlled.

Structural specifications of numerical  
25 examples are shown in Table 18. In this example, an  
image side working distance of 37 mm is assured, and  
the total glass material length along the optical path

is extraordinarily shortened to 286.8 mm. While the largest diameter of the optical system as a whole is 442 mm at the field optical system, the largest diameter of the second imaging system is small as 165 mm, regardless of that the NA is 0.6. Figure 42 shows aberrations, with respect to the base wavelength 157 nm and a wavelength rang of 4 pm. From the drawing, it is seen that aberrations are corrected satisfactorily.

10 [Example 19]

Figure 26 is an optical path view of Example 18 of the present invention. The design base wavelength was 157 nm of  $F_2$  excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was 1:5. The lens conjugate distance  $L$  was 934 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 7.7 mm to 14.0 mm. The optical system was provided by use of four mirrors and ten lenses.

20 In this example, denoted at  $r1 - r10$  are components of a first imaging system  $Gr1$ , and it comprises positive lenses ( $G1$ ) at  $r1$  and  $r2$ ; and  $r3$  and  $r4$ , negative lenses  $LN1$  at  $r5$  and  $r6$ ; and  $r8$  and  $r9$  of the same type, a first mirror  $M1$  (concave surface) and a second mirror  $M2$  (concave surface).  
25 Denoted at  $r11 - r18$  are components of a field optical system  $Grf$ , and it comprises a positive lens  $FL1$ , a

first field mirror FM1 (concave surface), a second field mirror FM2 (convex surface), and positive lenses LF at r14 and r15; and r17 and r18 of the same type. Denoted at r19 - r29 are components of a second  
5 imaging system Gr2, and it comprises a stop r19, four positive lenses and one negative lens.

In this example, with use of the first mirror group GM1 as provided by the negative lens LN1 and the first mirror M1, color correction is accomplished.

10 Further, with use of the second field mirror group GFM2 which is provided by the second field mirror FM2 (convex) and the positive lens LF, the Petzval sum is also controlled. Since the magnification of the first imaging system Gr1 is at the most reduction rate, a  
15 value close to the upper limit of condition (9) is taken. Since the spacing between the second and first field mirrors FM2 and FM1 is relatively small, a value close to the lower limit of condition (14) is taken.

Structural specifications of numerical  
20 examples are shown in Table 19. In this example, an image side working distance of 33.7 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 264.4 mm. Further, the largest diameter of the whole optical system is  
25 very short as 293 mm, and also the largest diameter of the second imaging system is small as 130 mm, regardless of that the NA is 0.6. Figure 43 shows

aberrations, with respect to the base wavelength 157 nm and a wavelength rang of 2 pm. From the drawing, it is seen that aberrations are corrected satisfactorily.

5 [Example 20]

Figure 27 is an optical path view of Example 20 of the present invention. The design base wavelength was 157 nm of F<sub>2</sub> excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was  
10 1:8. The lens conjugate distance L was 1190 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 9.56 mm to 13.65 mm. The optical system was provided by use of four mirrors and nine lenses,  
15 like Example 16.

In this example, denoted at r1 - r8 are components of a first imaging system Gr1, and it comprises a positive lens (G1) at r1 and r2, negative lenses LN1 at r3 and r4; and r6 and r7 of the same  
20 type, a first mirror M1 (concave surface) and a second mirror M2 (convex surface). Denoted at r9 - r16 are components of a field optical system Grf, and it comprises a positive lens FL1, a first field mirror FM1 (concave surface), a second field mirror FM2  
25 (convex surface), and negative lenses LF at r12 and r13; and r15 and r16 of the same type. Denoted at r17 - r27 are components of a second imaging system Gr2,

and it comprises a stop r17, four positive lenses and one negative lens.

In this example, since the magnification of the first imaging system Gr1 is strongly enlarged, a value close to the lower limit of condition (9) is taken. This is because the magnification of the first mirror group GM1 is positive, and because a value close to the upper limit of condition (13) is taken. As a result, a value close to the upper limit of condition (11) is taken, and the position of the intermediate image produced by the first imaging system Gr1 is far remote from the first mirror M1. Further, since the pupil conjugate point of the first imaging system Gr1 is at the image plane side with respect to the first mirror M1, a value close to the upper limit of condition (10) is taken. Additionally, with use of the second field mirror group GFM2 which is provided by the second field mirror FM2 (convex) and the negative lens LF, the Petzval sum is also controlled.

Structural specifications of numerical examples are shown in Table 20. In this example, an image side working distance of 36 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 315.5 mm. While the largest diameter of the optical system as a whole is 355 mm at the field optical system, the largest

diameter of the second imaging system is small as 177 mm, regardless of that the NA is 0.6. Figure 44 shows aberrations. From the drawing, it is seen that aberrations are corrected satisfactorily.

5 [Example 21]

Figure 28 is an optical path view of Example 21 of the present invention. The design base wavelength was 157 nm of F<sub>2</sub> excimer laser light, the NA was 0.6, and the projection magnification  $\beta$  was  
10 1:10. The lens conjugate distance L was 1190 mm. The optical system had an exposure region (imaging region) upon an image plane, of an arcuate shape, at the image height from 9.56 mm to 13.65 mm. The optical system was provided by use of four mirrors and nine lenses,  
15 like Example 16.

In this example, denoted at r1 - r8 are components of a first imaging system Gr1, and it comprises a positive lens (G1) at r1 and r2, negative lenses LN1 at r3 and r4; and r6 and r7 of the same  
20 type, a first mirror M1 (concave surface) and a second mirror M2 (convex surface which is substantially flat). Denoted at r9 - r16 are components of a field optical system Grf, and it comprises a positive lens FL1, a first field mirror FM1 (concave surface), a  
25 second field mirror FM2 (convex surface), and negative lenses LF at r12 and r13; and r15 and r16 of the same type. Denoted at r17 - r27 are components of a second



imaging system Gr2, and it comprises a stop rl7, four positive lenses and one negative lens.

In this example, the magnification of the second imaging system Gr2 has a value close to the lower limit of condition (1). Also, the distance between the second and first mirrors M2 and M1 is short, and a value close to the lower limit of condition (6) is taken. Further, with use of the first mirror group GM1 being provided by the negative lens LN1 and the first mirror M1 as well as the second field mirror group GFM2 which is provided by the second field mirror FM2 (convex) and the negative lens LF, the Petzval sum is also controlled.

Structural specifications of numerical examples are shown in Table 21. In this example, an image side working distance of 36 mm is assured, and the total glass material length along the optical path is extraordinarily shortened to 301.7 mm. While the largest diameter of the optical system as a whole is 310 mm at the field optical system, the largest diameter of the second imaging system is small as 180 mm, regardless of that the NA is 0.6. Figure 45 shows aberrations. From the drawing, it is seen that aberrations are corrected satisfactorily.

In Examples 5 - 21 described above, aspherical surfaces are used and, among the used aspherical surfaces, there are lens surfaces having a

conical constant  $k$  set to zero. However, design may be made while taking the conical constant  $k$  as a variable. Further, in these examples, the wavelength of an  $F_2$  excimer laser was used as a design wavelength, and fluorite ( $n = 1.5600$ ) was used as the glass material for it. However, any other glass material such as fluorine doped quartz, for example, may be used. Where a KrF or ArF light source is used, fluorite and quartz may be used in combination. Alternatively, only one of them may be used and, in that occasion, since the dispersion of glass material is smaller, the correction of chromatic aberration becomes easier.

A projection optical system according to these examples may be used as a projection optical system in a scan type projection exposure apparatus for projecting a pattern (device pattern such as a circuit pattern) of a reticle or a mask onto a substrate or a wafer in accordance with a step-and-scan procedure. A wafer is exposed to a device pattern by use of such exposure apparatus, and then, the exposure wafer is developed. Through subsequent processes such as etching, devices (semiconductor chips) are produced.

Structural specifications of numerical examples according to Examples 1 - 21 are shown in Tables 1 - 21 below.

In the numerical examples,  $r_1$  denotes the

curvature radius at the i-th lens surface, in an order from the object side,  $d_i$  is the i-th lens thickness or air spacing in an order from the object side, and  $n_i$  is the refractive index of the i-th lens glass, in an order from the object side, with respect to the base wavelength = 157 nm.

Further, the refractive indices of the wavelength +2pm and -2pm with respect to the base wavelength, are 1.5599949 and 1.5600051, respectively.

The shape of an aspherical surface can be given by the following equation:

$$X = \frac{H^2 / r_i}{1 + \left(1 - (1 + k) \cdot \left(H / r_i\right)^2\right)^{\frac{1}{2}}} + A \cdot H^4 + B \cdot H^6 + C \cdot H^8 + D \cdot H^{10} + E \cdot H^{12} + F \cdot H^{14} + G \cdot H^{16} + \dots$$

where X is the amount of displacement from the lens vertex along the optical axis direction, H is the distance from the optical axis,  $r_i$  is the curvature radius, k is the conical constant, and A, B, ... and G are aspherical coefficients.

TABLE 1: EXAMPLE 1

FIRST OBJECT TO FIRST SURFACE DISTANCE: 83.739 mm

5	i	ri	di	ni	
	1	989.392	18.000	1.56000	
	2	-3595.508	1.697		
	3	236.000	24.359	1.56000	
	4	2462.140	300.511		
	5	-114.548	18.000	1.56000	
	6	-946.909	7.879		
	7	-185.804	-7.879		
	8	-948.909	-18.000	1.56000	M 1
	9	-114.548	-286.511		
	10	1428.922	324.390		M 2
	11	380.000	48.405	1.56000	
	12	-345.892	434.726		
	13	102.426	18.000	1.56000	
10	14	225.926	45.944		
	15	0.0(stop)	21.343		
	16	2291.779	28.288	1.56000	
	17	-232.971	1.000		
	18	68.389	22.403	1.56000	
	19	275.504	1.000		
	20	139.927	19.297	1.56000	
	21	275.224	5.771		
	22	-963.793	27.452	1.56000	
	23	-228.789	1.000		
	24	106.934	18.000	1.56000	
	25	-742.488			
15	aspherical surfaces				
	i	K	A	B	C
	2	0.00000e+000	3.268074e-008	-5.656739e-012	1.084352e-016
	4	0.00000e+000	-5.945159e-008	9.367805e-012	-3.875872e-016
	5	0.00000e+000	-1.045454e-008	9.094085e-013	4.644093e-017
	7	0.00000e+000	-1.020658e-008	-2.127267e-013	-2.970263e-017
	9	0.00000e+000	-1.045454e-008	9.094085e-013	4.644093e-017
	12	0.00000e+000	1.276943e-008	-3.269379e-014	-1.148753e-018
	13	0.00000e+000	-1.177280e-007	-9.735382e-012	-5.058594e-016
	16	0.00000e+000	7.415847e-008	-1.533594e-011	2.908683e-015
	18	-2.765242e-001	-4.548406e-009	8.093119e-012	-1.772233e-015
20	20	-3.452390e+000	-1.157411e-007	-3.193404e-011	-1.695026e-015
	22	0.00000e+000	1.441342e-007	1.875541e-011	8.365199e-015
	24	-5.937621e-001	-2.497358e-007	-8.672718e-011	-1.119851e-014
					-1.058646e-017
	i	E	F	G	
	2	2.506755e-024	-9.840963e-029	0.000000e+000	
	4	-1.827522e-024	7.013708e-029	0.000000e+000	
	5	-1.953400e-022	2.716627e-026	0.000000e+000	
	7	-2.877088e-023	3.146892e-027	0.000000e+000	
	9	-1.963400e-022	2.716627e-026	0.000000e+000	
	12	-9.175707e-027	1.629370e-031	0.000000e+000	
	13	1.160369e-023	-1.219551e-027	0.000000e+000	
	16	-2.557773e-022	5.424698e-026	0.000000e+000	
	18	3.623462e-022	-1.873085e-025	0.000000e+000	
25	20	2.639407e-022	-5.908244e-025	0.000000e+000	
	22	7.408468e-021	-4.850248e-025	0.000000e+000	
	24	1.051653e-020	-1.104395e-023	0.000000e+000	

TABLE 2: EXAMPLE 2

FIRST OBJECT TO FIRST SURFACE DISTANCE: 75.685 mm

5	i	ri	di	ni	
	1	297.627	19.775	1.56000	
	2	-1115.696	328.484		
	3	-160.548	18.000	1.56000	
	4	2147.160	22.180		
	5	-203.139	-22.180		M 1
	6	2147.160	-18.000	1.56000	
	7	-160.548	-313.164		
	8	0.000	365.344		M 2
	9	1040.329	38.055	1.56000	
	10	-387.846	1.000		
	11	190.260	45.524	1.56000	
	12	634.071	120.149		
	13	249.471	18.000	1.56000	
10	14	127.136	325.385		
	15	0.0(stop)	1.000		
	16	234.780	33.014	1.56000	
	17	-336.281	1.000		
	18	144.606	35.000	1.56000	
	19	968.534	16.804		
	20	-793.316	35.000	1.56000	
	21	-100.000	1.000		
	22	88.381	25.000	1.56000	
	23	0.000			

15 aspherical surfaces

	i	K	A	B	C	D
	1	0.000000e+000	1.372961e-008	3.473252e-013	-3.195720e-016	9.094243e-020
	3	0.000000e+000	2.151239e-008	9.541648e-012	4.776084e-016	7.380865e-020
	5	0.000000e+000	4.532898e-009	1.823606e-012	1.222571e-016	1.631434e-020
	7	0.000000e+000	2.151239e-008	9.541648e-012	4.776084e-016	7.380865e-020
	10	0.000000e+000	5.040814e-010	2.625973e-013	-1.989714e-017	9.422664e-022
	11	0.000000e+000	-5.072499e-009	1.389868e-013	-1.647184e-017	3.468047e-022
	14	0.000000e+000	3.310157e-008	2.186614e-012	3.087404e-016	-3.918557e-020
	17	0.000000e+000	1.858529e-007	1.966297e-011	2.828536e-015	2.203369e-019
	20	0.000000e+000	-1.667572e-007	-3.379925e-011	7.374563e-015	-5.503285e-019
	22	0.000000e+000	-4.993819e-008	7.233187e-012	-2.042203e-015	3.653495e-020
20	i	E	F	G		
	1	-1.434764e-023	1.206555e-027	-4.210407e-032		
	3	-2.063590e-023	4.825958e-027	-5.593776e-031		
	5	-8.711867e-025	2.964757e-028	1.525109e-033		
	7	-2.063590e-023	4.825958e-027	-5.593776e-031		
	10	-2.700833e-026	4.650686e-031	-4.262218e-036		
	11	3.873194e-028	-2.799981e-031	4.425078e-037		
	14	1.130858e-023	-1.107497e-027	6.460332e-032		
	17	1.188890e-022	-2.552801e-026	7.612208e-030		
	20	1.402677e-023	2.115981e-027	-8.027962e-031		
	22	-2.309114e-022	-5.309629e-026	5.804270e-030		

25

TABLE 3: EXAMPLE 3

FIRST OBJECT TO FIRST SURFACE DISTANCE: 72.674

i	ri	di	ni	
1	-593.057	25.376	1.56000	
2	-320.774	1.000		
3	463.082	27.632	1.56000	
4	-613.991	281.867		
5	-109.249	18.000	1.56000	
6	-961.687	9.159		
7	-178.361	-9.159		M 1
8	-961.687	-18.000	1.56000	
9	-109.249	-266.071		
10	1622.171	305.230		M 2
11	-1660.654	24.024	1.56000	
12	-365.238	1.000		
13	347.111	47.000	1.56000	
14	-1881.176	410.002		
15	8178.667	25.178	1.56000	
16	-212.848	75.049		
17	0.0(stop)	15.536		
18	268.041	33.816	1.56000	
19	-186.462	1.000		
20	87.102	20.173	1.56000	
21	350.675	1.000		
22	156.475	21.218	1.56000	
23	86.116	6.639		
24	168.945	20.602	1.56000	
25	-165.909	1.000		
26	105.283	20.915	1.56000	
27	-743.988			

  

i	K	A	B	C	D
2	-7.252390e+000	-4.701121e-009	-5.090134e-013	-1.267089e-017	8.029170e-022
4	0.000000e+000	-4.765887e-008	2.462294e-012	-9.893034e-017	6.719603e-021
5	0.000000e+000	2.116808e-009	-1.611319e-013	1.025091e-015	5.091150e-019
7	0.000000e+000	-6.712584e-009	-8.093063e-013	2.887582e-017	9.870124e-020
9	0.000000e+000	2.116808e-009	-1.611319e-013	1.025091e-015	5.091150e-019
10	0.000000e+000	7.054971e-010	2.418241e-014	1.839107e-018	-7.963029e-023
12	0.000000e+000	4.707819e-009	-2.189427e-014	1.973642e-018	-1.068343e-023
13	0.000000e+000	8.092928e-010	-6.294695e-014	1.454461e-018	1.870403e-023
15	0.000000e+000	-1.344505e-007	1.853632e-012	1.650439e-016	-1.056871e-020
18	5.660213e+000	2.805319e-008	-5.963359e-011	5.837059e-017	8.483480e-019
20	-5.463452e-001	-1.335770e-007	-8.743479e-013	4.818362e-015	2.569222e-020
22	-1.401348e+000	-4.899966e-008	2.339115e-011	-1.429818e-014	-1.677957e-018
24	0.000000e+000	3.153044e-007	-8.376396e-012	1.928547e-014	-5.705932e-018
26	6.648275e-001	-1.189888e-007	6.781855e-012	-1.430235e-014	3.880028e-018

  

i	E	F	G
2	-4.085486e-025	1.924786e-029	0.000000e+000
4	-2.271393e-025	1.177205e-030	0.000000e+000
5	-1.657547e-023	6.847636e-027	0.000000e+000
7	-1.029026e-023	8.654760e-028	0.000000e+000
9	-1.657547e-023	6.847636e-027	0.000000e+000
10	4.433871e-028	2.201312e-032	0.000000e+000
12	-2.065745e-027	5.118720e-032	0.000000e+000
13	-3.513181e-027	7.676071e-032	0.000000e+000
15	-1.436354e-025	-9.351577e-030	0.000000e+000
18	-2.758585e-022	2.006196e-026	0.000000e+000
20	-2.770524e-022	-8.035716e-026	0.000000e+000
22	1.983183e-021	-1.380364e-025	0.000000e+000
24	-4.390899e-023	5.287086e-026	0.000000e+000
26	3.573891e-021	2.151859e-025	0.000000e+000

TABLE 4: EXAMPLE 4

FIRST OBJECT TO FIRST SURFACE DISTANCE: 81.211

5	i	ri	di	ni	
	1	2240.555	47.000	1.56000	
	2	-312.927	1.000		
	3	209.677	34.603	1.56000	
	4	-314.137	150.769		
	5	-819.717	-140.769		M 1
	6	277.686	889.917		M 2
	7	1806.318	19.445	1.56000	
	8	-583.025	1.000		
	9	0.0(stop)	73.850		
	10	197.078	35.504	1.56000	
	11	879.977	1.000		
10	12	126.409	28.494	1.56000	
	13	168.675	98.900		
	14	121.885	21.036	1.56000	
	15	905.776			

aspherical surfaces

	i	K	A	B	C	D
	2	0.000000e+000	3.706794e-008	-5.144019e-012	6.973326e-017	-7.330968e-021
	4	0.000000e+000	3.878903e-009	7.795334e-012	-6.781754e-016	5.265168e-020
15	5	0.000000e+000	8.445174e-009	3.143938e-011	-2.614011e-014	2.098089e-017
	6	0.000000e+000	-2.863861e-009	-5.305438e-015	1.717130e-018	-3.511472e-023
	7	0.000000e+000	-3.549063e-009	-1.408264e-013	1.931760e-019	5.091573e-023
10	10	0.000000e+000	-5.841539e-009	-2.405096e-013	4.288890e-018	-7.434790e-022
	12	0.000000e+000	-5.913583e-009	-4.340165e-014	-1.651705e-017	-1.294295e-022
	14	0.000000e+000	-8.534527e-008	-8.202426e-012	-7.411706e-016	-1.255475e-020
	i	E	F	G		
	2	7.818988e-025	-1.099803e-029	0.000000e+000		
	4	-3.124244e-024	7.960469e-029	0.000000e+000		
	5	-1.054713e-020	2.300997e-024	0.000000e+000		
	6	-1.813806e-028	5.037276e-032	0.000000e+000		
20	7	-4.316781e-027	8.877331e-032	0.000000e+000		
	10	2.311772e-026	-5.842989e-031	0.000000e+000		
	12	1.623655e-026	-3.143454e-030	0.000000e+000		
	14	-2.566756e-024	-3.831608e-028	0.000000e+000		

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TABLE 5: EXAMPLE 5

5	i	ri	di	ni	M1	Obj-distance= 281.857
	1	-276.517	-185.013	-1.0	M1	
	2	698.217	199.972		M2	
	3	507.773	48.488	1.56000	FL1	
	4	-238.848	9.987			
10	5	253.725	25.649	1.56000		
	6	544.261	258.577			
	7	-100.183	10.000	1.56000		
	8	-348.125	108.113			
	9	-205.877	10.000	1.56000		
	10	-302.653	9.696			
	11	0.0(stop)	11.356			$\beta = 1/6$
	12	388.065	23.350	1.56000		$L = 1005\text{mm}$
	13	-153.114	45.670			
	14	227.862	40.204	1.56000		
	15	-163.407	1.004			
	16	82.650	12.336	1.56000		$NA = 0.6$
	17	80.232	7.123			
	18	118.960	10.000	1.56000		
	19	54.261	1.597			
	20	56.346	44.698	1.56000		
	21	-655.354				

aspherical surfaces

15	i	K	A	B	C	D
	1	1.497949e+000	5.904355e-008	4.604214e-012	-6.840591e-016	-4.605410e-019
	2	3.802620e+000	-2.958077e-008	-4.331805e-013	-3.956055e-017	1.351662e-020
	3	0.000000e+000	-1.396795e-008	-2.011294e-013	9.452577e-019	3.436796e-022
	6	0.000000e+000	-5.231213e-009	-3.200408e-013	-7.768341e-018	3.291916e-022
	8	0.000000e+000	2.948640e-008	-6.137758e-012	-5.828601e-016	-1.299053e-019
	10	0.000000e+000	1.391954e-007	-1.481745e-011	-9.656666e-016	2.464643e-020
	13	0.000000e+000	9.98863e-008	1.676874e-011	-3.517423e-016	1.878125e-019
	14	0.000000e+000	-1.684359e-009	-1.027341e-011	-6.807870e-016	4.052904e-019
	16	0.000000e+000	-1.178575e-007	4.129293e-012	4.790552e-015	8.697392e-019
20	19	0.000000e+000	1.390299e-008	-3.249927e-010	-4.393543e-014	1.252755e-016
	20	0.000000e+000	2.089833e-007	-3.169110e-010	-5.080159e-014	1.188278e-016
	i	E	F	G		
	1	4.455248e-022	-9.166535e-026	0.000000e+000		
	2	-3.311509e-024	2.709386e-028	0.000000e+000		
	3	-1.264170e-026	1.297626e-031	0.000000e+000		
	6	2.676252e-027	-1.441611e-031	0.000000e+000		
	8	1.266055e-023	-2.859330e-027	0.000000e+000		
	10	6.808416e-024	2.160253e-027	0.000000e+000		
	13	-1.242980e-023	4.020013e-028	0.000000e+000		
	14	-4.999088e-023	2.234236e-027	0.000000e+000		
25	16	-4.361816e-022	6.665268e-026	0.000000e+000		
	19	-7.292427e-020	1.490664e-023	0.000000e+000		
	20	-6.999891e-020	1.483259e-023	0.000000e+000		



5

$$\beta = 1/5$$

$$NA = 0.6$$

10

15

2025

TABLE 7: EXAMPLE 7

5	i	ri	di	ni	Obj-distance= 50.000
	1	586.085	16.642	1.56000	
	2	-710.026	244.154		
	3	-293.735	-213.130	-1.0	M1
	4	634.175	224.502		M2
	5	692.102	18.310	1.56000	FL1
	6	-893.803	0.100		
	7	223.331	68.784	1.56000	
	8	726.029	73.396		
	9	244.650	29.831	1.56000	
	10	754.199	319.081		$\beta = 1/5$
	11	213.429	15.000	1.56000	$L = 1199\text{mm}$
	12	104.913	106.241		
	13	0.0(stop)	20.000		
10	14	712.703	86.305	1.56000	NA = 0.6
	15	-278.062	1.439		
	16	182.716	24.810	1.56000	
	17	-564.680	0.782		
	18	157.087	23.136	1.56000	
	19	1255.657	1.227		
	20	87.955	50.999	1.56000	
	21	123.472			

aspherical surfaces

15	i	K	A	B	C	D
	2	0.000000e+000	3.201613e-008	3.554666e-013	-3.442541e-016	8.565884e-020
	3	-1.672235e+000	2.280202e-008	-7.033732e-013	3.718998e-017	-2.862300e-021
	4	-1.049283e+000	1.235688e-008	-1.490507e-012	7.744144e-016	-3.612880e-019
	6	0.000000e+000	2.918278e-008	4.292516e-015	6.272355e-018	-7.663849e-022
	9	0.000000e+000	1.320709e-008	-8.609941e-013	1.501924e-017	-1.136497e-021
	12	0.000000e+000	1.980383e-007	2.532422e-011	1.138382e-015	4.147537e-019
	15	0.000000e+000	-1.871714e-008	-6.639558e-012	2.887450e-016	-2.996064e-020
	16	0.000000e+000	-3.265199e-008	-6.424945e-012	-9.334562e-016	5.226456e-020
	18	0.000000e+000	-2.362902e-008	-2.527146e-012	1.656380e-015	2.693269e-020
	21	0.000000e+000	2.563403e-008	-8.361181e-011	-1.336716e-015	7.803202e-018

20	i	E	F	G
	2	-1.071073e-023	5.207120e-028	0.000000e+000
	3	1.492277e-025	-2.707991e-030	0.000000e+000
	4	9.419452e-023	-9.922151e-027	0.000000e+000
	6	4.479081e-026	-7.629337e-031	0.000000e+000
	9	4.453112e-026	-1.452102e-030	0.000000e+000
	12	2.365835e-023	1.782122e-026	0.000000e+000
	15	2.959532e-024	-6.298400e-029	0.000000e+000
	16	3.674846e-026	1.155101e-028	0.000000e+000
	18	-6.493817e-024	-4.440784e-028	0.000000e+000
	21	3.786297e-022	-7.589609e-025	0.000000e+000

25

TABLE 8: EXAMPLE 8

5	i	rl	dl	ni	Obj-distance= 50.000
	1	283.541	20.452	1.56000	
	2	-1053.836	121.738		
	3	387.920	5.000	1.56000	
	4	229.873	124.483		
10	5	-291.999	-124.483	-1.0	M1
	6	229.873	-5.000	-1.56	
	7	387.920	-91.603	-1.0	
	8	881.192	91.603		M2
	9	387.920	5.000	1.56000	
	10	229.873	134.534		
	11	1316.372	24.857	1.56000	FL1
	12	-643.793	0.100		
	13	290.336	45.391	1.56000	
	14	-3338.651	27.518		
15	15	268.455	38.225	1.56000	
	16	708.139	372.871		
	17	145.801	15.000	1.56000	
	18	87.306	105.457		
	19	0.0(stop)	20.000		
	20	794.943	80.807	1.56000	
	21	-245.392	1.206		
	22	219.487	25.203	1.56000	
	23	-440.290	0.297		
	24	156.783	20.641	1.56000	
20	25	3004.077	0.391		
	26	91.029	52.047	1.56000	
	27	147.896			
	aspherical surfaces				
	i	K	A	B	C
	2	0.000000e+000	1.670163e-008	-7.564550e-013	7.640310e-017
	4	0.000000e+000	-2.210204e-008	3.815438e-012	-2.715457e-016
	5	-1.612890e+000	2.100848e-008	2.048446e-013	-9.687279e-017
	6	0.000000e+000	-2.210204e-008	3.815438e-012	-2.715457e-016
	8	2.782076e+000	1.108410e-008	8.595356e-013	-4.263225e-017
	10	0.000000e+000	-2.210204e-008	3.815438e-012	-2.715457e-016
	12	0.000000e+000	4.440282e-009	-3.621140e-013	2.360928e-018
	15	0.000000e+000	-1.135774e-008	-4.288698e-013	6.421899e-018
	18	0.000000e+000	1.483922e-007	1.741862e-011	2.796320e-015
25	21	0.000000e+000	1.354475e-008	-3.828203e-012	-1.671056e-016
	22	0.000000e+000	-1.098866e-008	-2.113914e-012	-4.900979e-016
	24	0.000000e+000	-2.754027e-008	-3.324771e-012	1.073083e-015
	27	0.000000e+000	-2.478578e-008	1.119494e-011	-4.674713e-014
					1.755113e-017
	i	E	F	G	
	2	1.090188e-024	-5.939842e-029	0.000000e+000	
	4	-1.063676e-024	2.691088e-030	0.000000e+000	
	5	-5.265028e-025	1.391005e-029	0.000000e+000	
	6	-1.063676e-024	2.691088e-030	0.000000e+000	
	8	2.574157e-023	-2.657189e-027	0.000000e+000	
	10	-1.063676e-024	2.691088e-030	0.000000e+000	
	12	-7.574790e-027	1.413732e-031	0.000000e+000	
	15	2.852148e-028	7.381569e-032	0.000000e+000	
	18	8.679435e-024	1.093535e-026	0.000000e+000	
	21	-2.719953e-024	1.131354e-028	0.000000e+000	
	22	2.024346e-025	-8.88050e-029	0.000000e+000	
	24	-1.099840e-023	2.651758e-028	0.000000e+000	
	27	-5.370134e-021	8.559204e-025	0.000000e+000	

$\beta = 1/5$   
 $L = 1198\text{mm}$   
 $NA = 0.6$

TABLE 9: EXAMPLE 9

i	ri	di	ni	Obj-distance= 51.000
1	-1815.127	22.814	1.56000	
2	-265.701	21.300		
3	1292.112	34.549	1.56000	LP1
4	-329.343	239.736		
5	-126.569	15.000	1.56000	LN1
6	1807.475	23.600		
7	-187.707	-23.600	-1.0	M1
8	1807.475	-15.000	-1.56	LN1
9	-126.569	-239.736	-1.0	
10	-329.343	-24.549	-1.56	LP1
11	1292.112	-3.300	-1.0	
12	-816.892	3.300		M2
13	1292.112	34.549	1.56000	LP1
14	-329.343	292.223		
15	2351.512	15.834	1.56000	FL1
16	-927.736	0.100		
17	304.902	27.947	1.56000	
18	1478.904	10.000		
19	218.515	27.908	1.56000	
20	527.237	169.549		
21	276.804	10.000	1.56000	
22	96.885	178.224		
23	-147.170	10.000	1.56000	
24	2898.421	31.011		
25	415.702	30.726	1.56000	
26	-182.240	9.109		
27	0.0(stop)	45.578		
28	150.492	37.309	1.56000	
29	-287.624	7.977		
30	95.129	41.064	1.56000	
31	116.210	15.986		
32	91.034	43.273	1.56000	
33	-471.423			

$$\beta = 1/5$$

$$L = 1166\text{mm}$$

$$NA = 0.6$$

aspherical surfaces

i	K	A	B	C	D
2	0.00000e+000	5.530494e-008	1.163655e-012	-6.262393e-017	-2.629751e-021
4	0.00000e+000	-1.892175e-008	4.266967e-013	1.121436e-017	-3.030043e-021
5	0.00000e+000	1.663615e-007	9.890835e-012	-1.309392e-015	6.427099e-019
7	9.165216e-004	2.675984e-008	1.316128e-012	2.694592e-017	-3.337487e-020
9	0.00000e+000	1.663615e-007	9.890835e-012	-1.309392e-015	6.427099e-019
10	0.00000e+000	-1.892175e-008	4.266967e-013	1.121436e-017	-3.030043e-021
12	5.000000e-000	-9.389111e-009	1.539504e-013	9.799722e-018	-2.247802e-021
14	0.00000e+000	-1.892175e-008	4.266967e-013	1.121436e-017	-3.030043e-021
16	0.00000e+000	1.255592e-008	-2.238808e-013	5.818116e-017	-7.054083e-021
17	0.00000e+000	4.718829e-009	-5.145083e-013	7.657683e-017	-9.189123e-021
22	0.00000e+000	-1.928999e-007	-1.154247e-011	4.702416e-017	-5.121045e-020
23	0.00000e+000	-3.035320e-007	-1.933933e-011	-2.138991e-015	-4.900557e-019
28	0.00000e+000	2.223625e-008	5.913986e-012	-1.487766e-016	4.859542e-020
29	0.00000e+000	1.714079e-008	1.681607e-012	-6.712043e-016	5.005422e-020
31	0.00000e+000	-1.372556e-008	7.658069e-011	-5.828110e-015	1.273953e-018
32	0.00000e+000	-5.643649e-007	1.451319e-011	-6.462196e-016	-3.490119e-019

  

i	E	F	G
2	6.200738e-025	-2.301378e-029	0.000000e+000
4	1.639180e-025	-3.981772e-030	0.000000e+000
5	-2.796760e-022	4.335286e-026	0.000000e+000
7	-4.892624e-024	1.494940e-027	0.000000e+000
9	-2.796760e-022	4.335286e-026	0.000000e+000
10	1.639180e-025	-3.981772e-030	0.000000e+000
12	1.259049e-025	-3.92339e-030	0.000000e+000
14	1.639180e-025	-3.981772e-030	0.000000e+000
16	4.425044e-025	-1.068897e-029	0.000000e+000
17	5.661917e-025	-1.358877e-029	0.000000e+000
22	6.968981e-024	-1.633272e-027	0.000000e+000
23	6.415923e-023	-3.082374e-026	0.000000e+000
26	-3.316785e-024	1.932364e-028	0.000000e+000
28	-2.320660e-024	6.485526e-029	0.000000e+000
31	-4.331702e-023	6.899488e-027	0.000000e+000
32	2.192732e-022	-3.646738e-026	0.000000e+000

TABLE 10: EXAMPLE 10

i	ri	di	ni	Obj-distance= 50.835
1	146.528	21.753	1.56000	
2	279.100	29.521		
3	-775.358	24.514	1.56000	LP1
4	-290.509	319.854		
5	-127.746	15.000	1.56000	LN1
6	901.597	15.068		
7	-165.915	-15.068	-1.0	M1
8	901.597	-15.000	-1.56	M1
9	-127.746	-319.054	-1.0	
10	-290.509	-24.514	-1.56	LP1
11	-775.358	-2.093	-1.0	M2
12	-1091.384	2.093		
13	-775.358	24.514	1.56000	LP1
14	-290.509	366.602		
15	-729.668	23.975	1.56000	FL1
16	-353.516	16.059		
17	278.912	35.728	1.56000	
18	1301.137	10.000		
19	230.845	40.089	1.56000	
20	858.078	145.157		
21	-1139.792	10.000	1.56000	
22	209.297	153.635		
23	141.077	10.000	1.56000	
24	77.386	30.123		
25	291.198	29.071	1.56000	
26	-210.751	4.057		
27	0.0(stop)	21.331		
28	204.073	51.876	1.56000	
29	-109.375	0.559		
30	220.520	21.237	1.56000	
31	552.592	4.737		
32	63.753	26.644	1.56000	
33	-13602.898			

$$\beta = 1/5$$

$$L = 1160\text{mm}$$

$$NA = 0.6$$

aspherical surfaces

i	K	A	B	C	D
2	0.000000e+000	8.655896e-008	-1.231783e-012	1.505671e-016	-1.994882e-020
4	0.000000e+000	-2.107372e-008	5.599304e-013	-3.486775e-017	4.285967e-021
5	0.000000e+000	1.483901e-007	-9.642930e-012	-1.428407e-016	-3.220462e-019
7	-1.883904e-001	3.492160e-008	2.674541e-013	-1.521679e-017	-4.134260e-020
9	0.000000e+000	1.483901e-007	-9.642930e-012	-1.428407e-016	-3.220462e-019
10	0.000000e+000	-2.107372e-008	5.599304e-013	-3.486775e-017	4.285967e-021
12	-3.641713e+000	-1.337813e-008	6.093453e-013	-2.932265e-017	3.056970e-021
14	0.000000e+000	-2.107372e-008	5.599304e-013	-3.486775e-017	4.285967e-021
16	0.000000e+000	-1.271307e-008	1.326186e-012	-6.548673e-017	2.762947e-021
19	0.000000e+000	-2.542101e-008	1.512560e-012	-8.198475e-017	3.416616e-021
22	0.000000e+000	-1.103975e-007	6.579457e-012	-1.251416e-016	-1.137648e-020
23	0.000000e+000	-6.584060e-007	-9.731531e-011	-4.923089e-015	-1.676955e-018
26	0.000000e+000	-2.178389e-007	-1.364187e-011	1.018419e-014	-1.147459e-018
28	0.000000e+000	-1.274240e-007	-3.607152e-011	8.050135e-015	-1.032749e-018
31	0.000000e+000	6.891976e-008	9.356366e-012	3.785313e-016	3.015742e-018
32	0.000000e+000	-1.469212e-007	-7.784012e-012	-3.664705e-015	3.444260e-018

i	E	F	G
2	2.274640e-024	-9.987248e-029	0.000000e+000
4	-2.059611e-025	2.643547e-031	0.000000e+000
5	6.834179e-023	-3.369361e-027	0.000000e+000
7	4.884293e-024	-2.923001e-028	0.000000e+000
9	6.834179e-023	-3.369361e-027	0.000000e+000
10	-2.059611e-025	2.643547e-031	0.000000e+000
12	-1.865907e-025	2.516890e-030	0.000000e+000
14	-2.059611e-025	2.643547e-031	0.000000e+000
16	-7.218715e-026	8.926086e-031	0.000000e+000
19	-9.166937e-026	1.136094e-030	0.000000e+000
22	3.478710e-024	-1.372775e-028	0.000000e+000
23	1.557766e-021	-4.766741e-025	0.000000e+000
26	1.658131e-022	9.278466e-027	0.000000e+000
28	9.644428e-023	-4.735347e-027	0.000000e+000
31	-7.985615e-022	1.332556e-025	0.000000e+000
32	-5.454904e-022	-8.938622e-026	0.000000e+000

TABLE 11: EXAMPLE 11

	i	ri	di	ni	Obj-distance= 50.962	
	1	549.485	18.225	1.56000		
	2	-348.358	404.377			
	3	-117.591	15.000	1.56000	LN1	
5	4	-11246.509	21.694			
	5	-181.192	-21.694	-1.0	M1	
	6	-11246.509	-15.000	-1.56	LN1	
	7	-117.591	-352.697	-1.0		
	8	-2026.523	-18.862	-1.56	LP1	
	9	461.050	-4.621	-1.0		
	10	-376.405	4.621			
	11	461.050	18.862	1.56000	M2	
	12	-2026.523	398.890		LP1	
	13	1172.423	42.790	1.56000	FL1	
	14	-501.353	0.404			
	15	315.855	47.177	1.56000		
	16	1252.990	3.907			
	17	200.947	27.209	1.56000		
	18	240.640	296.917			
10	19	-192.453	10.000	1.56000		$\beta = 1/4$
	20	602.106	179.501			$L = 1430\text{mm}$
	21	-186.356	10.000	1.56000		$NA = 0.6$
	22	438.885	32.245			
	23	541.516	30.056	1.56000		
	24	-149.805	8.704			
	25	0.0(stop)	45.181			
	26	179.275	33.860	1.56000		
	27	-370.567	9.275			
	28	94.992	43.811	1.56000		
	29	81.799	18.120			
	30	68.314	41.095	1.56000		
	31	-681.697				
15	aspherical surfaces					
	i	K	A	B	C	D
	1	0.00000e+000	4.575380e-008	7.817822e-013	-5.883907e-016	1.371733e-019
	3	0.00000e+000	1.832675e-008	-2.154592e-013	-1.520651e-016	-8.218511e-021
	5	8.415167e-001	1.155130e-008	1.103292e-013	-1.409211e-017	-1.720226e-021
	7	0.00000e+000	1.832675e-008	-2.154592e-013	-1.520651e-016	-8.218511e-021
	8	0.00000e+000	2.539857e-009	6.897518e-013	-2.706670e-016	2.977375e-020
	10	6.525900e-001	-3.453255e-010	6.892838e-013	-1.705759e-016	1.444644e-020
	12	0.00000e+000	2.539857e-009	6.897518e-013	-2.706670e-016	2.977375e-020
	14	0.00000e+000	-2.178001e-009	4.103517e-013	-1.817801e-017	5.715837e-022
	17	0.00000e+000	-1.282492e-008	3.641378e-013	7.085203e-019	0.000000e+000
	20	0.00000e+000	2.691714e-008	3.794681e-012	-2.566752e-017	6.095086e-022
	21	0.00000e+000	-2.046928e-007	8.688717e-012	1.766293e-016	-1.533138e-020
20	24	0.00000e+000	1.946195e-008	5.791056e-012	-3.912959e-016	4.417233e-020
	26	0.00000e+000	2.141413e-009	-8.073433e-013	-6.990201e-016	6.444734e-020
	29	0.00000e+000	-2.143697e-008	3.327692e-011	-5.094587e-015	1.783172e-018
	30	0.00000e+000	-2.020052e-007	-8.522637e-012	-7.090867e-015	1.840499e-018
	i	E	F	G		
	1	-1.760415e-023	8.840230e-028	0.000000e+000		
	3	6.179683e-025	8.769913e-028	0.000000e+000		
	5	-5.814168e-026	4.284447e-029	0.000000e+000		
	7	6.179683e-025	8.769913e-028	0.000000e+000		
	8	-1.502713e-024	2.476219e-029	0.000000e+000		
	10	-1.403417e-025	-3.422820e-029	0.000000e+000		
	12	-1.502713e-024	2.476219e-029	0.000000e+000		
	14	-1.027112e-026	8.042716e-032	0.000000e+000		
	15	2.066558e-026	0.000000e+000	0.000000e+000		
25	17	-8.993226e-027	-1.018383e-031	0.000000e+000		
	20	6.283744e-024	-5.389611e-028	0.000000e+000		
	21	5.836557e-024	-1.386454e-027	0.000000e+000		
	24	-3.359010e-024	9.801933e-029	0.000000e+000		
	26	-3.453019e-024	7.077619e-029	0.000000e+000		
	29	-4.057529e-022	2.495099e-026	0.000000e+000		
	30	-1.434595e-021	-8.941485e-027	0.000000e+000		

TABLE 12: EXAMPLE 12

i	rl	d	ni	Obj-distance= 63.346
1	973.794	19.006	1.56000	
2	-274.730	408.564		
3	-117.937	15.000	1.56000	LN1
4	-21944.448	22.129		
5	-183.531	-22.129	-1.0	M1
6	-21944.448	-15.000	-1.56	LN1
7	-117.937	-391.508	-1.0	
8	-2342.325	-16.507	-1.56	LP1
9	447.067	-0.506	-1.0	
10	-376.377	0.506		M2
11	447.067	16.507	1.56000	LP1
12	-2342.325	373.416		
13	1097.080	47.121	1.56000	FL1
14	-515.510	27.362		
15	280.430	47.913	1.56000	
16	718.618	7.108		
17	198.349	27.611	1.56000	
18	249.428	300.922		
19	-216.473	10.000	1.56000	
20	445.322	181.217		
21	-171.590	10.000	1.56000	
22	666.307	32.257		
23	625.617	30.422	1.56000	
24	-151.533	8.609		
25	0.0(stop)	47.280		
26	180.626	36.149	1.56000	
27	-335.594	9.318		
28	100.005	44.237	1.56000	
29	88.936	17.909		
30	70.805	41.541	1.56000	
31	-1049.267			

$$\beta = 1/4$$

$$L = 1430\text{mm}$$

$$NA = 0.6$$

aspherical surfaces

i	K	A	B	C	D
1	0.000000e+000	4.255133e-008	1.395979e-013	-1.009633e-016	4.472929e-021
3	0.000000e+000	1.715982e-008	1.867849e-013	1.918570e-017	-5.826782e-020
5	8.550872e-001	1.081079e-008	1.551602e-013	7.022939e-018	-6.098034e-021
7	0.000000e+000	1.715982e-008	1.867849e-013	1.918570e-017	-5.826782e-020
8	0.000000e+000	3.098651e-009	2.787833e-013	-1.677261e-016	1.684901e-020
10	9.872928e-001	1.142429e-009	4.039291e-013	-8.905924e-017	4.728326e-021
12	0.000000e+000	3.098651e-009	2.787833e-013	-1.677261e-016	1.684901e-020
14	0.000000e+000	-8.058628e-009	5.469068e-013	-1.863316e-017	4.646973e-022
15	0.000000e+000	8.819915e-010	1.397884e-013	-9.400188e-019	0.000000e+000
17	0.000000e+000	-1.822365e-008	3.451273e-013	-2.486759e-017	4.418373e-022
20	0.000000e+000	3.055326e-008	4.873760e-012	2.383916e-016	-6.806035e-021
21	0.000000e+000	-1.728562e-007	1.235438e-011	8.006503e-016	-6.090344e-020
24	0.000000e+000	3.819315e-008	6.635548e-012	-2.544128e-016	3.425391e-020
26	0.000000e+000	5.160883e-009	-9.687870e-013	-5.829555e-016	5.807106e-020
29	0.000000e+000	-8.273895e-009	2.804783e-011	-4.590743e-015	2.375151e-018
30	0.000000e+000	-1.430127e-007	-8.553894e-012	-7.235770e-015	4.163768e-018

  

i	E	F	G
1	1.933908e-024	-3.573554e-028	0.000000e+000
3	9.440074e-024	1.973849e-028	0.000000e+000
5	4.929424e-025	1.438389e-029	0.000000e+000
7	9.440074e-024	1.973849e-028	0.000000e+000
8	-7.086691e-025	6.530829e-030	0.000000e+000
10	2.776075e-025	-3.188109e-029	0.000000e+000
12	-7.086691e-025	6.530829e-030	0.000000e+000
14	-6.797904e-027	4.401325e-032	0.000000e+000
15	1.176176e-027	0.000000e+000	0.000000e+000
17	-5.160404e-027	-1.986704e-031	0.000000e+000
20	7.977247e-024	-8.335599e-028	0.000000e+000
21	-4.004980e-024	-5.894950e-028	0.000000e+000
24	-2.492308e-024	4.150762e-029	0.000000e+000
26	-3.458190e-024	9.835304e-029	0.000000e+000
29	-7.369796e-022	6.477749e-026	0.000000e+000
30	-2.463212e-021	2.053279e-025	0.000000e+000

TABLE 13: EXAMPLE 13

5						
	i	ri	di	ni		Obj-distance= 385.595
	1	-459.459	-335.573	-1.0	M1	
	2	3067.293	748.381		M2	
	3	-739.933	-391.713	-1.0	FM1	
	4	-573.829	392.713		FM2	
	5	0.0(stop)	60.000			
	6	-130.197	54.213	1.56000		
	7	-119.178	0.100			
	8	117.405	51.990	1.56000		
	9	519.563	6.291			
	10	78.099	41.649	1.56000		
10	11	1057.227	0.100			
	12	1050.175	15.000	1.56000		
	13	87.469	11.904			$\beta = 1/5$
	14	326.920	29.310	1.56000		$L = 1100\text{mm}$
	15	-1292068.739				$NA = 0.6$

aspherical surfaces

	i	K	A	B	C	D
15	1	2.151232e+000	2.074850e-008	1.028497e-012	1.000198e-016	-1.543777e-020
	2	1.565028e+000	-1.030439e-008	-8.656324e-014	1.017720e-017	-3.830427e-021
	3	-1.579007e-001	-1.873321e-010	-2.793967e-016	-3.564540e-021	7.688159e-026
	4	-1.552277e+000	-9.150769e-009	-8.581363e-014	-1.464695e-017	2.978012e-021
	7	0.000000e+000	-1.113320e-008	6.313114e-012	-4.925043e-016	6.437342e-020
	8	0.000000e+000	5.404994e-009	-2.805582e-012	1.463407e-016	-4.789462e-020
	10	0.000000e+000	-1.606239e-007	1.691804e-012	-2.762745e-015	1.781576e-019
	13	0.000000e+000	2.498212e-007	1.350239e-011	2.359108e-014	5.612084e-019
	14	0.000000e+000	4.979099e-007	-1.344689e-010	4.588479e-014	-2.537504e-017
	i	E	F	G		
20	1	3.311515e-024	-2.995664e-028	0.000000e+000		
	2	5.161873e-025	-2.729459e-029	0.000000e+000		
	3	-1.127394e-030	7.746168e-036	0.000000e+000		
	4	-3.412103e-025	1.755156e-029	0.000000e+000		
	7	-4.171136e-024	1.891343e-028	0.000000e+000		
	8	4.264568e-024	-3.356973e-028	0.000000e+000		
	10	-4.525225e-023	-2.846830e-028	0.000000e+000		
	13	-2.105753e-021	1.040548e-024	0.000000e+000		
	14	7.650574e-021	-1.459197e-024	0.000000e+000		



TABLE 14: EXAMPLE 14

i	ri	di	ni	Obj-distance= 397.959
1	-447.799	-347.959	-1.0	M1
2	11489.229	811.432		M2
3	-804.784	-422.009	-1.0	FM1
4	-1121.103	-15.000	-1.56	LF
5	-431.869	-5.561	-1.0	
6	-1235.236	5.561		FM2
7	-431.869	15.000	1.56000	LF
8	-1121.103	423.009		
9	0.0(stop)	55.691		
10	-128.913	19.560	1.56000	
11	-108.272	0.309		
12	124.318	28.713	1.56000	
13	694.622	0.100		
14	78.512	42.819	1.56000	
15	219.566	9.184		
16	-741.750	15.000	1.56000	
17	92.545	14.848		
18	73.579	20.344	1.56000	
19	-2120.514			

$\beta = /5$   
 $L = 1100\text{mm}$   
 $NA = 0.6$

## 15 aspherical surfaces

i	K	A	B	C	D
1	1. 651069e+000	2. 374926e-008	1. 702835e-012	1. 390779e-017	2. 614732e-020
2	-4. 000000e+000	-1. 043013e-008	-1. 517620e-013	4. 986190e-018	-2. 371680e-021
3	-7. 638388e-002	-1. 823532e-010	-2. 150504e-016	-1. 108786e-021	1. 340316e-025
6	-3. 827967e+000	-8. 674101e-009	-1. 051516e-013	-5. 752138e-018	6. 145431e-022
11	0. 000000e+000	4. 892931e-008	-5. 416482e-013	5. 381903e-016	1. 678633e-020
12	0. 000000e+000	7. 048042e-008	2. 284679e-012	-9. 626527e-016	3. 338522e-019
14	0. 000000e+000	-3. 924140e-008	-8. 582640e-012	1. 843538e-015	-3. 326077e-019
17	0. 000000e+000	8. 970756e-007	3. 402220e-011	3. 720934e-014	1. 395150e-017
18	0. 000000e+000	7. 110875e-007	-5. 771239e-011	5. 210874e-014	-9. 240921e-018

  

i	E	F	G
1	-7. 722632e-024	7. 560718e-028	0. 000000e+000
2	2. 760856e-025	-1. 354385e-029	0. 000000e+000
3	-1. 379314e-031	5. 943291e-037	0. 000000e+000
6	-5. 871993e-026	2. 213211e-030	0. 000000e+000
11	-6. 073286e-024	6. 405299e-028	0. 000000e+000
12	-4. 157626e-023	2. 508234e-027	0. 000000e+000
14	2. 612172e-024	2. 192107e-027	0. 000000e+000
17	-5. 673999e-021	3. 032464e-024	0. 000000e+000
18	6. 249971e-021	9. 050086e-031	0. 000000e+000

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TABLE 15: EXAMPLE 15

i	ri	di	ni	Obj-distance= 50.000
1	204.213	15.833	1.56000	
2	3825.784	413.292		
3	-106.572	15.000	1.56000	LN1
4	-857.552	17.304		
5	-187.562	-17.304	-1.0	M1
6	-857.552	-15.000	-1.56	LN1
7	-106.572	-408.626	-1.0	
8	-1909.161	951.629		M2
9	-858.848	-459.710	-1.0	FM1
10	-214.544	-26.074	-1.56	LF
11	-423.622	-4.701	-1.0	
12	-291.919	4.701		FM2
13	-423.622	26.074	1.56000	LF
14	-214.544	400.010		
15	0.0(stop)	59.759		
16	424.663	15.005	1.56000	
17	-637.707	0.101		
18	135.307	20.950	1.56000	
19	482.071	0.101		
20	86.180	31.425	1.56000	$\beta = 1/4$
21	180.516	9.606		$L = 1190\text{mm}$
22	108.812	15.000	1.56000	$NA = 0.6$
23	55.211	16.293		
24	82.713	23.334	1.56000	
25	-343.416			

aspherical surfaces

i	K	A	B	C	D
1	0.000000e+000	7.845851e-008	3.480979e-012	-2.192632e-016	2.652275e-020
2	0.000000e+000	1.287363e-007	5.213100e-012	-3.909292e-016	-2.757054e-020
3	0.000000e+000	5.511695e-008	2.742398e-012	2.976607e-016	-8.135784e-020
5	9.757356e-001	2.245223e-008	4.961650e-013	4.876359e-017	-9.218124e-021
7	0.000000e+000	5.511695e-008	2.742398e-012	2.976607e-016	-8.135784e-020
8	-2.324211e-001	-3.741519e-009	-2.965745e-014	3.165593e-019	-1.721869e-022
9	-1.351560e-001	-4.438792e-012	4.120307e-018	6.561688e-023	1.639361e-026
10	0.000000e+000	1.134555e-008	-5.474633e-013	-1.044929e-016	1.349222e-020
12	2.922694e+000	2.325940e-008	-2.396438e-013	-1.043028e-016	2.382476e-020
14	0.000000e+000	1.134555e-008	-5.474633e-013	-1.044929e-016	1.349222e-020
16	0.000000e+000	-5.994350e-008	-4.756412e-012	-8.685536e-017	-1.026534e-019
18	0.000000e+000	-8.290830e-008	-4.984870e-012	1.936271e-015	8.131779e-021
20	0.000000e+000	4.860989e-008	1.213638e-011	-2.550341e-015	9.673512e-020
23	0.000000e+000	-4.300839e-007	-3.408055e-011	-3.710689e-015	-2.158579e-018
24	0.000000e+000	-3.101203e-007	-4.766363e-011	1.545142e-015	1.795645e-020

  

i	E	F	G
1	-1.461145e-023	1.281999e-027	0.000000e+000
2	0.000000e+000	0.000000e+000	0.000000e+000
3	3.995845e-023	-2.211509e-027	0.000000e+000
5	3.224225e-024	-1.287665e-028	0.000000e+000
7	3.995845e-023	-2.211509e-027	0.000000e+000
8	1.248827e-026	-4.508298e-032	0.000000e+000
9	-3.247603e-031	1.929812e-036	0.000000e+000
10	-5.294016e-025	-6.522725e-030	0.000000e+000
12	-1.683354e-024	3.413090e-029	0.000000e+000
14	-5.294016e-025	-6.522725e-030	0.000000e+000
16	2.849939e-023	-2.173374e-027	0.000000e+000
18	-3.631059e-023	2.226964e-027	0.000000e+000
20	-3.275165e-023	5.637523e-027	0.000000e+000
23	-3.457497e-021	4.909090e-025	0.000000e+000
24	-1.908395e-021	8.087019e-025	0.000000e+000

TABLE 16: EXAMPLE 16

i	ri	di	ni	Obj-distance= 50.267
1	282.936	21.255	1.56000	
2	3684.211	449.103		
3	-267.457	15.000	1.56000	LN1
4	-1371.221	5.446		
5	-321.384	-5.446	-1.0	M1
6	-1371.221	-15.000	-1.56	LN1
7	-267.457	-338.525	-1.0	
8	-1540.132	368.971		M2
9	440.699	35.890	1.56000	FL1
10	-1887.670	362.966		
11	-922.802	-332.666	-1.0	FM1
12	8422.125	-15.000	-1.56	LF
13	-462.452	-5.300	-1.0	
14	-1026.228	5.270		FM2
15	-462.452	15.000	1.56000	LF
16	8422.125	268.193		
17	0.0(stop)	64.503		
18	237.890	23.809	1.56000	
19	2990.697	12.038		
20	135.928	34.579	1.56000	$\beta = 1/5$
21	622.051	3.846		$L = 1190\text{mm}$
22	144.391	38.185	1.56000	$NA = 0.6$
23	205.170	2.454		
24	114.728	15.000	1.56000	
25	72.687	9.881		
26	78.971	64.113	1.56000	
27	2179.982			

aspherical surfaces

i	K	A	B	C	D
1	0.000000e+000	4.950479e-008	-1.556107e-012	1.719144e-017	2.105431e-021
3	0.000000e+000	-5.113917e-009	-2.873876e-012	2.602766e-017	6.788996e-020
5	7.999895e-001	-1.716298e-009	-1.163867e-012	2.214635e-018	2.170496e-020
7	0.000000e+000	-5.113917e-009	-2.873876e-012	2.602766e-017	6.788996e-020
8	5.000000e+000	3.994191e-009	-6.866541e-014	-1.799842e-018	-3.213142e-023
9	0.000000e+000	-4.745677e-009	9.727308e-015	-1.323010e-019	1.552321e-024
11	-3.742879e-001	-9.987061e-011	-8.267759e-016	2.319422e-020	-3.735582e-026
12	0.000000e+000	1.256240e-008	2.224328e-012	-1.743188e-015	1.674418e-019
14	3.922730e+000	-2.955486e-008	-3.015675e-013	-1.303534e-015	8.709164e-020
16	0.000000e+000	1.256240e-008	2.224328e-012	-1.743188e-015	1.674418e-019
20	0.000000e+000	-4.228533e-008	-1.756337e-012	-1.341137e-016	-8.216530e-021
22	0.000000e+000	1.397442e-008	-6.652675e-013	1.180182e-016	1.951605e-020
25	0.000000e+000	4.243718e-008	1.008140e-011	-5.060486e-016	-5.298502e-020
26	0.000000e+000	-1.152710e-007	4.633120e-012	-7.184290e-016	-1.928268e-019

  

i	E	F	G
1	0.000000e+000	0.000000e+000	0.000000e+000
3	0.000000e+000	0.000000e+000	0.000000e+000
5	0.000000e+000	0.000000e+000	0.000000e+000
7	0.000000e+000	0.000000e+000	0.000000e+000
8	0.000000e+000	0.000000e+000	0.000000e+000
9	0.000000e+000	0.000000e+000	0.000000e+000
11	0.000000e+000	0.000000e+000	0.000000e+000
12	0.000000e+000	0.000000e+000	0.000000e+000
14	0.000000e+000	0.000000e+000	0.000000e+000
16	0.000000e+000	0.000000e+000	0.000000e+000
20	0.000000e+000	0.000000e+000	0.000000e+000
22	0.000000e+000	0.000000e+000	0.000000e+000
25	0.000000e+000	0.000000e+000	0.000000e+000
26	0.000000e+000	0.000000e+000	0.000000e+000

TABLE 17: EXAMPLE 17

i	ri	di	ni	Obj-distance=	64.302
1	145.868	15.654	1.56000		
2	277.033	421.902			
3	-331.764	15.000	1.56000	LN1	
4	427.187	37.533			
5	-243.163	-37.533	-1.0	M1	
6	427.187	-15.000	-1.56	LN1	
7	-331.764	-400.174	-1.0		
8	-1050.590	462.707		M2	
9	1082.335	45.592	1.56000	FL1	
10	-506.181	419.093			
11	-556.173	-340.231	-1.0	FM1	
12	890.632	-49.792	-1.56	LF	
13	129.563	-12.279	-1.0		
14	503.066	12.279		FM2	
15	129.563	49.792	1.56000	LF	
16	890.632	308.936			
17	0.0(stop)	34.831			
18	212.603	15.000	1.56000		$\beta = 1/4$
19	358.696	0.100			$L = 1188\text{mm}$
20	154.082	17.867	1.56000		$NA = 0.6$
21	14558.550	0.107			
22	233.915	24.251	1.56000		
23	-182.460	0.246			
24	102.219	15.000	1.56000		
25	70.401	6.731			
26	78.313	40.387	1.56000		
27	-274.349				

aspherical surfaces

i	K	A	B	C	D
1	0.000000e+000	-4.543384e-008	2.008795e-013	-5.987597e-017	-7.178408e-022
3	0.000000e+000	-1.396774e-008	-1.312696e-012	-4.099589e-017	-1.204130e-021
5	2.136452e+000	7.442417e-009	1.308120e-013	2.191394e-018	-3.414108e-023
7	0.000000e+000	-1.396774e-008	-1.312696e-012	-4.099589e-017	-1.204130e-021
8	3.674765e-001	-5.080134e-009	-2.169803e-013	-7.383666e-018	-2.178985e-022
9	0.000000e+000	-3.096618e-009	6.122886e-015	-3.324130e-020	-2.496687e-026
11	-6.480972e-001	7.109927e-010	-3.912529e-015	3.016030e-021	-2.009020e-027
13	0.000000e+000	-1.535424e-008	-4.271143e-013	-5.423533e-017	2.156146e-021
14	-2.947254e-001	1.369848e-009	-1.353039e-013	1.572367e-017	-1.209804e-021
15	0.000000e+000	-1.535424e-008	-4.271143e-013	-5.423533e-017	2.156146e-021
20	0.000000e+000	-1.254255e-007	-3.689620e-012	-1.110656e-015	1.994369e-019
22	0.000000e+000	-1.374196e-007	-1.437806e-011	3.602627e-015	-3.618777e-019
25	0.000000e+000	8.431891e-008	-2.787295e-011	-9.578735e-015	-5.255927e-018
26	0.000000e+000	7.697163e-008	1.013236e-011	-6.851146e-015	-4.256775e-018

  

i	E	F	G
1	0.000000e+000	0.000000e+000	0.000000e+000
3	0.000000e+000	0.000000e+000	0.000000e+000
5	0.000000e+000	0.000000e+000	0.000000e+000
7	0.000000e+000	0.000000e+000	0.000000e+000
8	0.000000e+000	0.000000e+000	0.000000e+000
9	0.000000e+000	0.000000e+000	0.000000e+000
11	0.000000e+000	0.000000e+000	0.000000e+000
13	0.000000e+000	0.000000e+000	0.000000e+000
14	0.000000e+000	0.000000e+000	0.000000e+000
15	0.000000e+000	0.000000e+000	0.000000e+000
20	0.000000e+000	0.000000e+000	0.000000e+000
22	0.000000e+000	0.000000e+000	0.000000e+000
25	0.000000e+000	0.000000e+000	0.000000e+000
26	0.000000e+000	0.000000e+000	0.000000e+000

TABLE 18: EXAMPLE 18

i	ri	di	ni	Obj-distance= 51.375
1	294.105	24.410	1.56000	
2	-2765.072	417.053		
3	-116.294	15.000	1.56000	LN1
4	-2872.831	20.722		
5	-186.216	-20.722	-1.0	M1
6	-2872.831	-15.000	-1.56	LN1
7	-116.294	-383.291	-1.0	
8	-1505.962	429.623		
9	444.041	63.934	1.56000	M2 FL1
10	-3099.408	334.815		
11	-948.436	-300.896	-1.0	FM1
12	-314.227	-16.435	-1.56	LF
13	-824.068	-7.484	-1.0	
14	-325.089	7.484		
15	-824.068	16.435	1.56000	FM2 LF
16	-314.227	301.796		
17	0.0(stop)	55.267		
18	654.524	17.101	1.56000	
19	-493.112	0.100		
20	127.646	36.817	1.56000	
21	9721.169	9.587		
22	124.513	19.292	1.56000	
23	107.027	11.036		
24	94.369	15.000	1.56000	
25	93.351	9.999		
26	115.073	47.374	1.56000	
27	-373.527			

$\beta = 1/4$   
 $L = 1197\text{mm}$   
 $NA = 0.6$

15 aspherical surfaces

i	K	A	B	C	D
1	0.000000e+000	3.270469e-008	-2.618357e-012	4.062834e-016	-5.211535e-020
3	0.000000e+000	4.411046e-009	-5.444659e-013	-4.482642e-017	1.266365e-019
5	9.780048e-001	1.163827e-008	2.616720e-013	-9.065597e-019	1.119604e-020
7	0.000000e+000	4.411046e-009	-5.444659e-013	-4.482642e-017	1.266365e-019
8	-1.539537e+000	3.786900e-009	-9.453622e-014	3.248795e-018	-2.012056e-022
9	0.000000e+000	-4.149266e-009	2.307771e-015	-1.751852e-021	-1.213130e-024
11	-3.776756e+000	-4.342111e-010	-2.394400e-015	5.496039e-020	-1.406823e-024
12	0.000000e+000	-1.673853e-009	-3.281730e-012	6.683323e-016	-8.393102e-020
14	-3.600157e+000	-3.076829e-008	-3.309550e-012	6.132785e-016	-1.002042e-019
16	0.000000e+000	-1.673853e-009	-3.281730e-012	6.683323e-016	-8.393102e-020
19	0.000000e+000	1.130381e-008	1.048332e-012	-2.689716e-016	1.609677e-020
20	0.000000e+000	-2.363339e-008	-1.791151e-012	-4.488565e-016	-3.302356e-020
22	0.000000e+000	4.460228e-009	-2.267365e-012	-2.653562e-016	2.051402e-020
25	0.000000e+000	3.016193e-007	2.151092e-011	-3.603828e-016	-2.089239e-018
26	0.000000e+000	2.718387e-007	2.254954e-011	-7.855692e-016	-2.167393e-018

  

i	E	F	G
1	3.766459e-024	-1.147383e-028	0.000000e+000
3	-1.676440e-023	2.206450e-027	0.000000e+000
5	-9.520370e-025	9.545144e-029	0.000000e+000
7	-1.676440e-023	2.206450e-027	0.000000e+000
8	1.042016e-026	-2.633116e-031	0.000000e+000
9	1.190683e-029	-3.996052e-035	0.000000e+000
11	1.831918e-029	-9.562670e-035	0.000000e+000
12	4.958336e-024	-1.328994e-028	0.000000e+000
14	7.328052e-024	-3.110175e-028	0.000000e+000
16	4.958336e-024	-1.328994e-028	0.000000e+000
19	-7.303308e-025	3.915870e-029	0.000000e+000
20	-6.049533e-025	-2.110230e-029	0.000000e+000
22	5.955447e-023	-4.660843e-027	0.000000e+000
25	7.756637e-022	-7.997079e-027	0.000000e+000
26	7.445927e-022	-4.578951e-026	0.000000e+000

TABLE 19: EXAMPLE 19

i	ri	di	ni	Obj-distance= 51.000
1	351.655	16.754	1.56000	
2	-8365.385	1.500		
3	200.954	22.369	1.56000	
4	591.866	247.671		
5	-88.814	15.000	1.56000	LN1
6	-402.056	7.000		
7	-151.144	-7.000	-1.0	M1
8	-402.056	-15.000	-1.56	LN1
9	-88.814	-240.671	-1.0	
10	1366.187	349.374		M2
11	19831.441	26.737	1.56000	FL1
12	-735.739	244.705		
13	-566.816	-219.048	-1.0	FM1
14	-133.579	-14.510	-1.56	LF
15	-205.618	-1.148	-1.0	
16	-202.153	1.148		FM2
17	-205.618	14.510	1.56000	LF
18	-133.579	224.997		
19	0.0(stop)	-4.929		
20	-119.907	20.312	1.56000	
21	-246.626	7.094		
22	153.705	24.772	1.56000	
23	-385.679	18.913		
24	97.386	43.291	1.56000	
25	177.767	7.651		
26	95.442	31.717	1.56000	
27	364.058	6.848		
28	103.255	19.448	1.56000	
29	-1048.656			

$\beta = 1/5$   
 $L = 934\text{mm}$   
 $NA = 0.6$

aspherical surfaces

i	K	A	B	C	D
1	0.000000e+000	-8.093313e-008	4.522834e-012	-2.018073e-016	2.267148e-020
3	0.000000e+000	6.511812e-008	-3.723599e-012	1.013032e-016	-2.501488e-021
5	0.000000e+000	2.476497e-008	-5.194074e-012	2.934576e-014	-6.771024e-018
7	-8.634921e-002	5.766118e-008	1.400403e-011	1.171617e-014	-2.406379e-018
9	0.000000e+000	2.476497e-008	-5.194074e-012	2.934576e-014	-6.771024e-018
10	3.403605e+000	-2.532676e-009	4.911669e-014	1.807856e-018	-2.255506e-022
13	-5.700272e-001	1.734919e-010	1.781213e-015	-7.464135e-021	1.125815e-024
14	0.000000e+000	6.268611e-009	9.790240e-013	5.096073e-017	-4.749646e-020
16	-9.969546e-001	4.762518e-009	8.200176e-013	6.576997e-018	-5.959712e-020
18	0.000000e+000	6.268611e-009	9.790240e-013	5.096073e-017	-4.749646e-020
21	0.000000e+000	7.500151e-008	-2.370496e-011	-1.965330e-015	3.913950e-019
23	0.000000e+000	-5.983025e-009	2.383340e-011	-4.396313e-016	-2.197526e-019
24	0.000000e+000	4.080007e-008	-9.297261e-012	1.873727e-015	-1.418320e-019
26	0.000000e+000	-3.783040e-007	-1.883182e-012	-8.030466e-016	-7.057718e-019
28	0.000000e+000	-9.452418e-008	-1.957493e-011	-1.244651e-014	0.000000e+000

  

i	E	F	G
1	-3.670991e-024	2.228767e-028	0.000000e+000
3	1.383272e-024	-1.154892e-028	0.000000e+000
5	4.483389e-021	-9.723939e-025	0.000000e+000
7	8.068244e-022	-6.319119e-026	0.000000e+000
9	4.483389e-021	-9.723939e-025	0.000000e+000
10	1.792109e-026	-6.218030e-031	0.000000e+000
13	-3.288087e-029	4.085249e-034	0.000000e+000
14	1.007847e-023	2.645246e-029	0.000000e+000
16	1.769682e-023	-1.119411e-027	0.000000e+000
18	1.007847e-023	2.645246e-029	0.000000e+000
21	-1.267664e-023	-8.319497e-028	0.000000e+000
23	1.954211e-023	-3.173836e-029	0.000000e+000
24	1.171050e-023	-3.681475e-028	0.000000e+000
26	8.165762e-023	1.411746e-026	0.000000e+000
28	-2.398432e-022	-4.378158e-025	0.000000e+000

TABLE 20: EXAMPLE 20

i	ri	di	ni	Obj-distance= 50.000
1	245.198	40.746	1.56000	
2	565.312	378.944		
3	-198.743	15.000	1.56000	LN1
4	-553.813	2.806		
5	-383.608	-2.806	-1.0	M1
6	-553.813	-15.000	-1.56	LN1
7	-198.743	-358.732	-1.0	
8	6976.362	386.889		M2
9	355.685	51.490	1.56000	FL1
10	-12321.788	369.283		
11	-1028.093	-343.512	-1.0	FM1
12	730.908	-15.000	-1.56	LF
13	-1511.630	-0.100	-1.0	
14	-1023.030	0.070		FM2
15	-1511.630	15.000	1.56000	LF
16	730.908	323.513		
17	0.0(stop)	39.007		
18	302.719	22.983	1.56000	
19	-6847.780	21.360		
20	145.723	31.514	1.56000	
21	618.670	8.713		
22	147.653	25.174	1.56000	$\beta = 1/8$
23	391.950	8.285		$L = 1190\text{mm}$
24	121.433	15.000	1.56000	$NA = 0.6$
25	80.944	14.809		
26	94.829	68.564	1.56000	
27	-806.611			

aspherical surfaces

i	K	A	B	C	D
1	0.000000e+000	2.707002e-008	-8.717359e-013	1.291774e-017	-8.046083e-023
3	0.000000e+000	-1.285216e-008	-4.644289e-012	-1.098284e-015	4.074896e-020
5	1.853481e+000	-5.942386e-009	-1.921556e-012	-3.991601e-016	3.066166e-020
7	0.000000e+000	-1.285216e-008	-4.644289e-012	-1.098284e-015	4.074896e-020
8	4.692105e+000	6.776075e-009	-1.213133e-013	2.083765e-018	-3.379785e-023
9	0.000000e+000	-7.268271e-009	3.352308e-015	-1.357278e-019	-1.824547e-024
11	1.213373e+000	-1.515625e-010	-6.598956e-015	2.230167e-019	-3.018642e-024
12	0.000000e+000	2.663004e-009	-5.964634e-012	-3.132031e-015	3.139422e-019
14	3.818120e+000	-5.339380e-008	-6.525763e-012	-2.026068e-015	1.112273e-019
16	0.000000e+000	2.663004e-009	-5.964634e-012	-3.132031e-015	3.139422e-019
20	0.000000e+000	-4.537132e-008	-1.444034e-012	-6.237537e-017	-1.225622e-020
22	0.000000e+000	2.258810e-008	-2.784423e-012	-4.694218e-017	4.207858e-020
25	0.000000e+000	1.033200e-007	-6.071918e-012	-2.759843e-015	-3.195258e-019
26	0.000000e+000	-2.135939e-008	-6.495251e-012	-2.642392e-015	-2.963340e-019

  

i	E	F	G
1	0.000000e+000	0.000000e+000	0.000000e+000
3	0.000000e+000	0.000000e+000	0.000000e+000
5	0.000000e+000	0.000000e+000	0.000000e+000
7	0.000000e+000	0.000000e+000	0.000000e+000
8	0.000000e+000	0.000000e+000	0.000000e+000
9	0.000000e+000	0.000000e+000	0.000000e+000
11	0.000000e+000	0.000000e+000	0.000000e+000
12	0.000000e+000	0.000000e+000	0.000000e+000
14	0.000000e+000	0.000000e+000	0.000000e+000
16	0.000000e+000	0.000000e+000	0.000000e+000
20	0.000000e+000	0.000000e+000	0.000000e+000
22	0.000000e+000	0.000000e+000	0.000000e+000
25	0.000000e+000	0.000000e+000	0.000000e+000
26	0.000000e+000	0.000000e+000	0.000000e+000

TABLE 21: EXAMPLE 21

i	ri	di	ni	Obj-distance= 50.487
1	248.654	45.879	1.56000	
2	2498.279	433.450		
3	-430.357	17.451	1.56000	LN1
4	1258.317	2.793		
5	-320.814	-2.793	-1.0	M1
6	1258.317	-17.451	-1.56	LN1
7	-430.357	-170.466	-1.0	
8	-566426.061	200.710		M2
9	-1563.039	37.005	1.56000	FL1
10	-250.953	361.172		
11	-765.976	-329.940	-1.0	FM1
12	244.884	-15.000	-1.56	LF
13	549.490	-6.231	-1.0	
14	-701.208	6.201		FM2
15	549.490	15.000	1.56000	LF
16	244.884	283.488		
17	0.0(stop)	46.600		
18	244.341	23.507	1.56000	
19	57346.724	0.100		
20	138.156	28.770	1.56000	
21	561.247	3.336		
22	145.732	37.036	1.56000	
23	260.318	4.990		
24	111.587	15.000	1.56000	
25	70.790	33.292		
26	75.408	49.617	1.56000	
27	5689.128			

$\beta = 1/10$   
 $L = 1190\text{mm}$   
 $NA = 0.6$

aspherical surfaces

i	K	A	B	C	D
1	0.000000e+000	-2.521478e-009	-8.451485e-014	5.214505e-019	-2.685571e-023
3	0.000000e+000	-3.993741e-008	2.044280e-012	1.954603e-014	4.016803e-018
5	4.706536e+000	-4.082512e-008	-1.158264e-011	7.155566e-015	-2.269483e-019
7	0.000000e+000	-3.993741e-008	2.044280e-012	1.954603e-014	4.016803e-018
8	5.000000e+000	-3.971095e-009	-7.223454e-014	-1.084017e-018	6.587792e-024
9	0.000000e+000	-4.759165e-009	1.313843e-014	1.109392e-019	-1.230866e-024
11	3.289899e-001	-3.568080e-010	-1.380316e-015	1.016681e-020	-6.587533e-026
12	0.000000e+000	-2.613402e-008	-9.198710e-013	-1.784868e-016	2.018156e-020
14	-4.000000e+000	-3.882997e-008	-1.433855e-012	-1.916913e-016	4.859577e-022
16	0.000000e+000	-2.613402e-008	-9.198710e-013	-1.784868e-016	2.018156e-020
20	0.000000e+000	-4.145601e-008	-2.245516e-012	-8.585230e-017	-7.216150e-021
22	0.000000e+000	1.029827e-008	-4.482490e-015	1.152103e-017	1.349052e-020
25	0.000000e+000	1.056111e-007	8.819533e-012	3.490901e-016	2.003722e-020
26	0.000000e+000	-3.282437e-008	3.472717e-012	-3.391125e-016	-1.465019e-019

  

i	E	F	G
1	0.000000e+000	0.000000e+000	0.000000e+000
3	0.000000e+000	0.000000e+000	0.000000e+000
5	0.000000e+000	0.000000e+000	0.000000e+000
7	0.000000e+000	0.000000e+000	0.000000e+000
8	0.000000e+000	0.000000e+000	0.000000e+000
9	0.000000e+000	0.000000e+000	0.000000e+000
11	0.000000e+000	0.000000e+000	0.000000e+000
12	0.000000e+000	0.000000e+000	0.000000e+000
14	0.000000e+000	0.000000e+000	0.000000e+000
16	0.000000e+000	0.000000e+000	0.000000e+000
20	0.000000e+000	0.000000e+000	0.000000e+000
22	0.000000e+000	0.000000e+000	0.000000e+000
25	0.000000e+000	0.000000e+000	0.000000e+000
26	0.000000e+000	0.000000e+000	0.000000e+000



While the invention has been described with  
reference to the structures disclosed herein, it is  
not confined to the details set forth and this  
application is intended to cover such modifications or  
5 changes as may come within the purposes of the  
improvements or the scope of the following claims.

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